AAMRL-TR-88-014

LOOP-CLOSURE OF THE VISUAL-CORTICAL RESPONSE (U)

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FEBRUARY 1988

SUMMARY REPORT FOR PERIOD
DECEMBER 1986 TO DECEMBER 1987

ARMSTRONG AEROSPACE MEDICAL RESEARCH LABORATORY
HUMAN SYSTEMS DIVISION
AIR FORCE SYSTEMS COMMAND
WRIGHT-PATTERSON AIR FORCE BASE, OHIO 45433-6573

UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1a. REPORT SECURITY CLASSIFICATION UNCLASSIFIED	1b. RESTRICTIVE MARKINGS
2a. SECURITY CLASSIFICATION AUTHORITY	3. DISTRIBUTION/AVAILABILITY OF REPORT Approved for public release; distribution is unlimited.
2b. DECLASSIFICATION/DOWNGRADING SCHEDULE	
4. PERFORMING ORGANIZATION REPORT NUMBER(S) AAMRL-TR-88-014	5. MONITORING ORGANIZATION REPORT NUMBER(S)
6a. NAME OF PERFORMING ORGANIZATION Harry G. Armstrong Aerospace Medical Research Laboratory 6b. OFFICE SYMBOL (If applicable) HEG	7a. NAME OF MONITORING ORGANIZATION
6c. ADDRESS (City, State, and ZIP Code) Wright-Patterson AFB OH 45433-6573	7b. ADDRESS (City, State, and ZIP Code)
8a. NAME OF FUNDING/SPONSORING ORGANIZATION 8b. OFFICE SYMBOL (If applicable)	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
8c. ADDRESS (City, State, and ZIP Code)	10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO	WORK UNIT ACCESSION NO.
61101F	7184	14	D1/D3

11. TITLE (Include Security Classification)

Loop-Closure of the Visual-Cortical Response (U)

12. PERSONAL AUTHOR(S)
Junker, Andrew M., Schnurer, John,* Ingle, David F.,* and Downey, Craig*

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
Summary	FROM Dec 86 TO Dec 87	1988 February	50

16. SUPPLEMENTARY NOTATION
*Systems Research Laboratories, Inc.
2800 Indian Ripple Road
Dayton OH 45440

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
05	08	
06	02	

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
Visual Evoked Response,
Frequency Response Analysis,
Loop-Closure ; Biofeedback ; (KT)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Results of a study designed to test the effectiveness of using feedback to consciously connect humans to their evoked response and thereby "close the loop" around the brain are presented. A technique to achieve loop closure using a lock-in amplifier approach is presented. Findings indicate that conscious control of EEG is possible. Each of the eight subjects tested was able to achieve control. Comparisons are made between loop-closure results and the human steady-state evoked potential (SSEP). The SSEP is obtained by recording and analyzing the visual evoked response to a sum-of-ten sine waves. This approach provides simultaneous multiple frequency measurements of the human EEG to the evoking stimulus in terms of describing functions (gain and phase) and remnant spectra. A relationship between the SSEP and loop-closure ability is discussed. Ways in which the SSEP quantities vary with the addition of a decision making task are also presented. Implications of these results in terms of secondary tasks for mental-state estimation and brain actuated control are addressed.

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT ☒ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT ☐ DTIC USERS	21. ABSTRACT SECURITY CLASSIFICATION UNCLASSIFIED
22a. NAME OF RESPONSIBLE INDIVIDUAL Dr Andrew M. Junker	22b. TELEPHONE (Include Area Code) (513) 255-8747 22c. OFFICE SYMBOL AAMRL/HEG

DD Form 1473, JUN 86 Previous editions are obsolete

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

PREFACE

The research summarized in this report was performed at the Workload and Ergonomics Branch of the Armstrong Aerospace Medical Research Laboratory, WPAFB, Ohio. Funding for this work came from the Laboratory Commanders Fund under WU# 718414D1 and WU# 718414D3. This represents the final report for this effort. The authors wish to express their thanks to the subjects who were willing to take a chance and "look within", creating loop-closure: Patricia, Susan, Merrill, Grace, and Diantha. The authors also wish to acknowledge Dr. Robert Northrop of the University of Connecticut for suggesting the use of lock-in amplifiers.

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1. INTRODUCTION

By using appropriate signal averaging techniques, it is possible to detect a response in the human electroencephalogram (EEG) to evoking stimuli. When the stimulus is sinusoidally modulated the result is called a steady state evoked potential (SSEP). Research in this area suggests that the SSEP may be a useful indicator for mental-state estimation (Spekreijse, 1966; Regan, 1972; Wilson and O'Donnell, 1980).

Using a light stimulus modulated by a sum of sine waves, a steady state evoked potential can be elicited that contains responses at all of the component frequencies of the driving stimulus. A technique has been developed to drive the stimulus with a 10 frequency sum of sines. This technique has been refined and upgraded to a level of sophistication that allows detailed analysis to be applied to the discrete Fourier transforms of the SSEP and the evoking stimulus. This analysis simultaneously produces describing function measures and background EEG spectra (Junker et al., 1987). The describing function provides gain and phase information as a function of stimulus frequency, measures which are systems engineering based. The background EEG spectrum, referred to as the remnant in this report, provides information about the average power adjacent to, but not including the power at, stimulus frequencies. Thus, this remnant represents an average measure of EEG activity excluding the linear response to the evoking stimulus.

This analysis has been applied to SSEPs in taskloading and non-taskloading conditions. The tasks used were manual tracking, grammatical reasoning and decision making (Junker et al., 1987).

The results of our previous research indicate that the obtained describing functions are sensitive to changes in task loading. SSEPs were found to be unique to each individual within the general classifications of alpha and non-alpha responders. Alpha and non-alpha responders refer to the strength of the evoked response and remnant response in the alpha band (8Hz to 12Hz) compared to responses in adjacent frequency areas. SSEPs were also found to be sensitive to levels of attention, especially in the alpha band.

These results were promising, however there is a difficulty with this and perhaps other evoked physiological measures that needs to be addressed. The visual-cortical response is an open loop measure. Unlike human performance in a manual control situation where an optimal behavior for best performance exists, the subject is not provided with an environment directing a certain response.

In our evoked response studies no performance feedback was provided. Subjects occasionally produced weak or unevoked responses which may have been from lack of attention due to distraction or fatigue. Based upon what was learned from our research in manual control experimentation (Levison, 1983; Levison et al., 1971; Levison and Junker, 1978), it was concluded that a closed-loop visual-cortical response paradigm could allow subjects to compensate for any detrimental factors and provide an improved response.

From our evoked response data it was observed that the evoked potentials in the frequency domain were as specific or as narrow as the measurement bandwidth of the experimental system being used, in our case 0.0244 Hz (Junker et al., 1987). Thus we concluded that frequency specificity of the feedback signal should be of concern.

If a feedback loop is to be effective it must also contain minimal lags and transport delays. EEG biofeedback trainers at the Menninger Foundation (personal communication) indicated that a biofeedback signal should not be delayed more than 4 cycles for it to be a useful signal from which subjects could learn to "control" their EEG.

From the above discussion, it was concluded that for the feedback signal to be effective it must be both timely and frequency specific. Useful feedback information about a 10 Hz response, for example, might require that there be no more than a 0.4 second delay in the feedback loop. To simultaneously achieve such a small delay and frequency specificity is not an easy task. For the work reported above, a frequency specificity of 0.0244 Hz was achieved, but only by analyzing 40.96 seconds of data at a time. Thus we concluded that concurrent frequency resolution and timeliness could not be achieved by our available digital system.

Furthermore, from manual control results it is known that human controllers can more efficiently compensate for lags in a system than pure time delays (such as would exist in a digital system) by deriving lead through extraction of rate and acceleration information from sensory displays. To obtain specific frequency information from an EEG, however, requires some method of frequency averaging to extract the signal from the noise. Knowing this, and based upon manual control results, it was decided to investigate an analog active-filter, rather than a digital computer, approach. In this way delays in the system produced by signal averaging would be principally transfer lags instead of pure time delays.

The active-filter approach consisted of using a Lock-in Amplifier System (LAS) for obtaining a continuous averaged frequency measure (gain and phase) at a specific 'locked in' frequency. The LAS can be extremely sensitive in detecting periodic signals of low amplitude and poor signal to noise ratio. The LAS equivalent response is that of a very sharply tuned band-pass filter. Other researchers have made use of LAS technology for measuring frequency responsiveness of the human EEG in an open loop context (Kaufman and Price, 1967; Regan and Cartwright, 1970; Hileman and Dick, 1971; Euler and Kiessling 1980; Nelson et al., 1984). The LAS consists of two quadrature phase sensitive detectors, the outputs of which are lowpass filtered and converted to polar form to yield continuous gain and phase measures of the signal at the lock-in frequency.

Loop closure was achieved by providing visual and audio feedback of the LAS. Subjects were simultaneously exposed to an evoking stimulus which was driven sinusoidally at the same frequency as that of the LAS clock. Subjects were instructed to either increase or decrease their LAS response provided to them via the two feedback signals.

The experimental procedure consisted of first obtaining SSEP responses from the subjects to be tested. Next, to determine the effectiveness of loop closure with feedback, four subjects were tested (two receiving "true" feedback and two receiving "false" feedback). During the final phase of the experiment all subjects were trained with true feedback. The results of this experimental effort are presented in this report.

2. METHODOLOGY

2.1 Steady-State Evoked Potential Measurement

The experimental apparatus used to obtain SSEP measures is illustrated in Figure 2.1. The apparatus consists of a stimulus presentation device which simultaneously delivered the evoking stimulus (flickering light) and a video task display. This presentation was achieved by combining the two images via a half-silvered mirror at 45 degrees to each image. The evoking stimulus was produced by two fluorescent light tubes behind a diffusing screen which distributed the light over the entire visual field. The intensity of the light was measured by a photocell placed in the subject's line of sight. The tasks were displayed on the video monitor. The average intensity of the evoking light was sufficiently low so that the subject could comfortably discern the video task display within the same visual field.

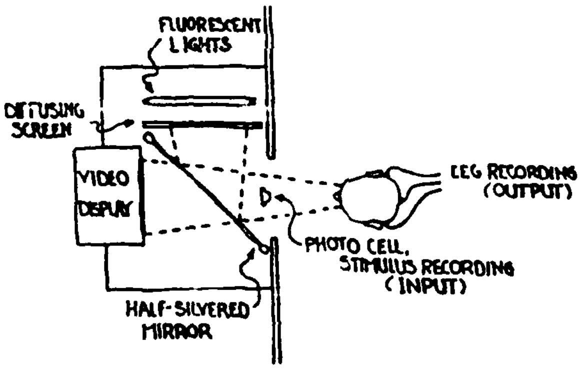


Figure 2.1. Experimental apparatus for SSEP measurements.

Subjects were seated in a darkened chamber facing the test apparatus. For the task conditions, subjects were instructed to concentrate on the tasks. At the end of each 90 second trial, the subject's performance score appeared on the screen. For the non-task condition, called lights only, subjects were instructed to "relax and fixate on the center of the screen". Sessions were limited to 20 trials.

The EEG was obtained by using gold cup electrodes with O1 as signal, P3 as reference and right ear as ground. For left handed subjects (Subject 03 in this study) O2 was used as signal, P4 as reference and left ear as ground. This technique was used for SSEP measurement and LAS loop-closure. Sum-of-sines generation and data collection were accomplished on a PDP 11/60 computer. The two channels of data (photocell and EEG) were filtered, digitized and stored for analysis. The collected data was discrete Fourier transformed, ensemble averaged, describing functions and remnant were computed, and the results were then plotted. Estimates of mean values for the gain and phase computations across trials were computed. For an indication of mean variability, standard errors were computed. The describing function gain (amplitude ratios of the EEG to photocell) indicates evoked response sensitivity at the component frequencies. The phase values relate to neurophysiological dynamics and transmission latency between photocell excitation and EEG measurement.

A decision making task with two levels of difficulty was used to elicit diverse cognitive states with the intention of evoking different visual-cortical responses. Input came from the video display and the output from subjects was produced by manual operation of push-buttons.

Decision making involved the problem of allocating attention among multiple tasks in a supervisory control system (Pattipati et. al., 1979). Subjects observed the video display on which multiple concomitant tasks were represented by moving rectangular bars. The bars appeared at the left edge of the screen and moved at different velocities to the right, disappearing upon reaching the right edge. At any given time there were, at most, five tasks displayed with a maximum of one on each line. The subjects could process a task by depressing the appropriate push-button. Once a button had been pushed, the computer remained dedicated to that task until task completion or the task ran off the screen. By processing a task successfully, the subject was credited with the corresponding reward, and the completed task was eliminated from the display. Two levels of difficulty were used. In the "easy" condition it was possible to successfully allocate attention among the multiple tasks. In the "hard" condition the time required exceeded the time available and it was not possible to complete all allocations successfully.

The sum-of-sines stimulus was composed of ten harmonically non-related multiples of the fundamental frequency of 0.0244 Hz. In addition, none of these component frequencies were equal to a sum or difference of any of the other component frequencies. This restriction on the sine wave frequency selection was implemented to avoid first order nonlinear interactions. The ten component frequencies were: 6.25, 7.73, 9.49, 11.49, 13.25, 14.74, 16.49, 18.25, 20.23, and 21.74 Hz. For every data collecting trial, starting phase values for each of the 10 component sine waves were randomized, ensuring that the time sequence of flickering light presentation was random from trial to trial. By utilizing randomized starting phase values with the summing of the 10 sinusoids a maximum depth of modulation of 13% per sinusoid was achieved. An average luminance of 40 foot-Lamberts was used as it provided an effective stimulus intensity and at the same time was not overly obtrusive to the decision making video display. For a detailed discussion of the rationale for designing sum-of-sines inputs the reader is referred to Junker et al., 1987.

2.2 Loop-Closure Of Subjects' EEG

A loop-closure system was developed that could extract specific frequency information from a subjects' EEG and present the information to the subject. The equipment simultaneously presented an evoking stimulus at the same frequency as that of the extracted EEG information. The approach involved using a tunable bandpass filter in combination with a Lock-in Amplifier System (LAS). A diagram for this system is presented in Figure 2.2. The LAS consists of two quadrature phase sensitive detectors (Analog Devices AD630 synchronous modulator/demodulator chips), the outputs of which are lowpass filtered (two pole equal valued Sallen-Key filters, unity gain, poles at 0.5 Hz) and converted to polar form using an xy-to-polar chip (Interface Engineering Inc., Model SA 860B) to yield continuous gain and phase signals at the lock-in frequency. The lock-in frequency is

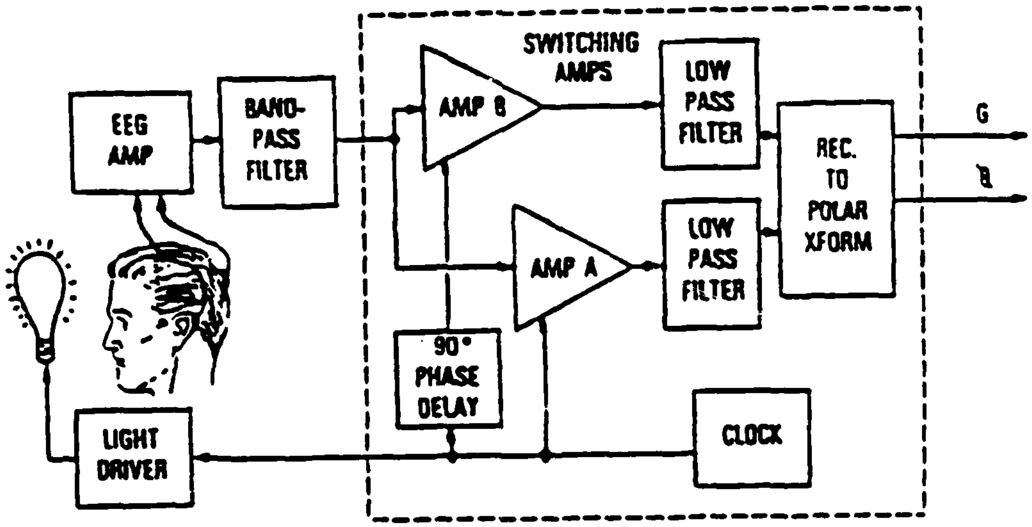


Figure 2.2. Lock-in Amplifier System block diagram.

determined by a clock (phase lock-loop with .001 Hz resolution) which generates a square wave, a quadrature square wave, and a sine wave. The square waves drive the phase sensitive detectors, amplifiers A and B. The sine wave is used to drive the light stimulus. The bandpass filter (Krohn-Hite Model 3750), tuned to the clock frequency, is used to improve the signal to noise ratio of the input to the LAS.

The LAS provides a continuous measure of gain and phase suggesting that it could be used in conjunction with steady-state stimulation to explore the time varying nature of task loading. A possible approach would be to use the SOS stimulus and continuously record the LAS output at one of the 10 SOS frequencies. Correlations between the continuous measure (LAS gain and/or phase) and the time varying nature of the task could be investigated. In the case of the decision making task this could be the times of appearance of new targets and times before or at the moment of button pushing.

To close the loop, using the LAS approach, it was necessary to provide feedback to subjects of their EEG production at the evoking frequency. The experimental setup used to accomplish this is illustrated in Figure 2.3. Feedback of EEG information was provided to subjects through two modes, a light bar display, and an amplitude modulated tone. The qualifications for tone selection were that it be

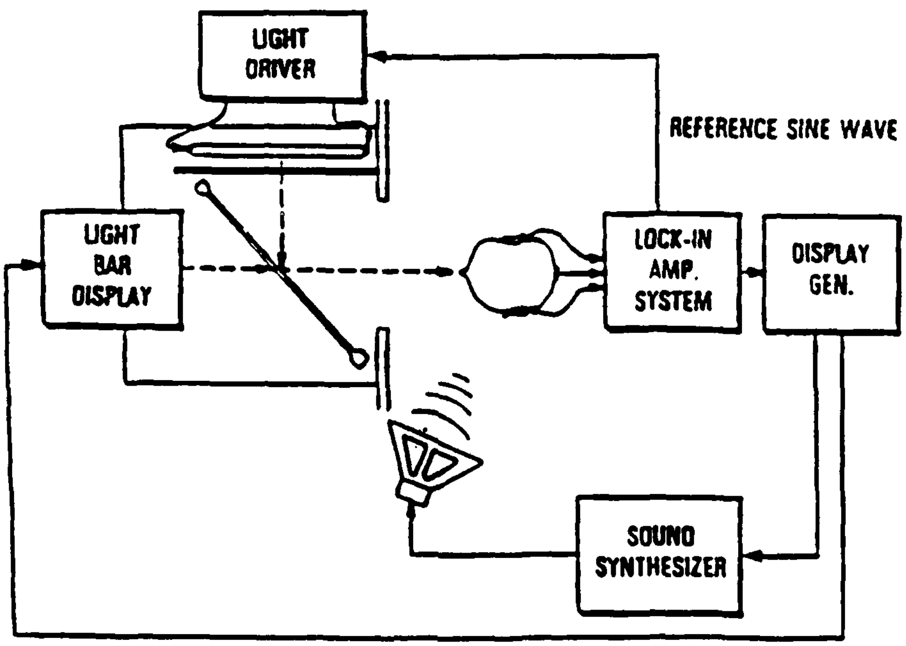


Figure 2.3. Experimental setup for loop-closure and feedback training.

harmonically related to the visual evoking stimulus frequency and 'pleasing' to the subject. Amplitude modulation of a harmonically related tone was chosen instead of frequency modulation because past research indicated that a strong relationship exists between amplitude modulated tones and amplitude modulated light (Erickson, 1974). Amplitude modulated tones of 106.0 Hz for 13.25 Hz and 61.8 Hz for 7.73 Hz were used in the experiment. These tones were equal to the third harmonic of the visual evoking stimulus. As the subject's EEG amplitude increased at the target frequency, indicated by an increase of the LAS gain signal, more light bars became lit and the volume of the tone increased.

The response of the LAS is equivalent to that of a sharply tuned band-pass filter. The responsiveness and frequency specificity of the LAS depends primarily upon the frequency characteristics of the LAS lowpass filters. With the lowpass filters set to 0.5 Hz, the frequency resolution or bandwidth of the LAS was determined to be approximately 0.45 Hz (down 3 dB from center frequency). The 0 to 95% rise time was 1.7 seconds and the 100 to 5% fall time was 1.2 seconds. As discussed in the introduction a response time of close to 0.4 seconds for training at 10 Hz would be marginally acceptable. Thus at first the LAS seems to have an unacceptable response time. However, upon closer inspection of the LAS response one sees that there is only a 0.2 second period in which there is no activity following the step input. In other words, even through the 0 to 95% rise time was 1.7 seconds, after the first 0.2 seconds some information will be fed back to the subjects (see Figure 2.4), thus allowing them to be cognizant of their EEG level. In addition these filter settings provide a reasonably narrow frequency specificity and thus appear to be the optimum values to use for the experimental protocol.

For feedback training it was decided to use frequencies that would hopefully reside within relatively quiet areas of the EEG spectrum. Therefore two frequencies were chosen, one below the alpha band and one between the alpha band and beta band. In addition, the two frequencies were selected from the 10 sinewaves used in the SOS stimulus so that describing function data would be available for subsequent comparisons. Therefore the frequencies of 7.73 Hz and 13.25 Hz were selected.

To provide comparable results between subjects for each frequency under investigation, the EEG response was adjusted to approximately the same level for each subject at the start of each session. A variable gain control of the EEG signal prior to the bandpass filter (refer to Figure 2.2) was used to achieve EEG gain adjustment. The result of this adjustment was determined by monitoring the subject's EEG spectrum with a Spectrum Analyzer (HP model 3582A) at the output of the variable gain control (input of LAS).

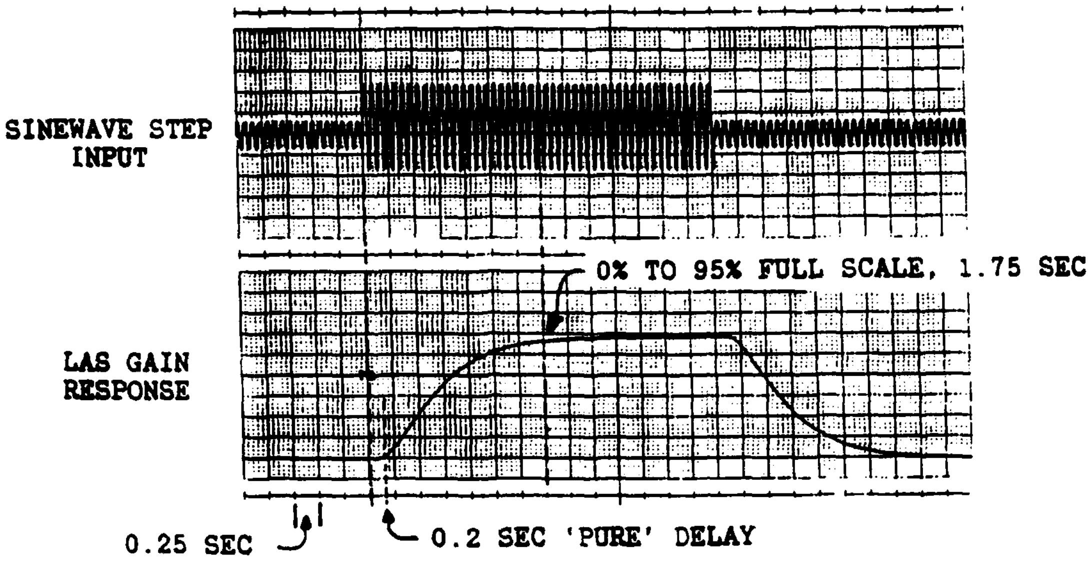


Figure 2.4. LAS time response to a 13.25 Hz sinewave step input.

During each experimental session subjects trained at both frequencies. The first half of the session consisted of training at one frequency and the next half at the second frequency. The task of the subject was to either increase the feedback signal or decrease the feedback signal over a 100 second trial. An experimental session consisted of a block of eight 100 sec trials for each frequency for a total of 2 blocks per session. Within each block of 8 trials, subjects were instructed to "raise the light bar" (increase the feedback signal) for 4 trials, and "lower the light bar" (decrease the signal) for 4 trials. The order of presentation of the two frequencies as well as the order of raising and lowering were randomized.

One mode of EEG control is the ability, at a given frequency, to hold signal amplitude above or maintain it below a predetermined threshold. The fifth light bar on a 16 light bar display was chosen as the threshold. Performance scoring was a measure of how many seconds, out of a 100 second trial, the subject's amplitude went above this fifth bar level. The second performance measure was the coherence between the subject's EEG and the evoking light stimulus. Coherence values were obtained from the HP model 3582A Spectrum Analyzer. For each block of eight trials, the average difference for each performance measure between increasing and suppressing the EEG signal was computed. This resulted in an average performance score and standard deviations for both increasing and suppressing EEG signals combined together for each block. Averaged values per block were then graphed for each subject. Plotted in each graph were the average values and the largest standard deviation (either from increasing or suppressing) per block. A value above the dashed line in each graph indicates for that block the average of the 4 'increasing' values was greater than the average of the 4 'suppressing' values. Values below the dashed line indicate that the opposite trend occurred.

To evaluate the effectiveness of using feedback to help learn control of one's evoked response the following two conditions were investigated. The first condition consisted of using the experimental setup as illustrated in Figure 2.3. One group of two subjects trained under this condition. For the second condition the experimental setup of Figure 2.3 was modified such that true EEG feedback was replaced with false feedback from an analog random noise generator. The noise was injected into the bandpass filter of the experimental apparatus instead of the subject's EEG. A second group of two subjects trained under this false feedback condition. These tests were performed to determine if evoked potential control could be mastered independent of external feedback. The four subjects, although aware of the possibility of getting either real or false feedback, were not informed until the experiment's conclusion as to which type of feedback they had received. After receiving 12 sessions of false feedback the subjects who received false feedback received true feedback for 8 sessions.

Four of the eight subjects were randomly selected to participate in this phase of the experiment. Two of the four subjects chosen were alpha producers and two were not. Subjects were randomly assigned to the two experimental groups with the constraint that the two alpha producers (Subjects 13 and 77 as determined by SSEP measurements) would not be in the same group. This resulted in Subjects 13 and 07 being assigned to the true feedback group and Subjects 77 and 03 to the false feedback group.

Once the above phase of experimental testing was completed, the remaining four subjects were run using the true feedback configuration. In addition the two subjects who received false feedback and then true feedback were run for an additional 4 sessions with true feedback so that all subjects received a total of 12 sessions of true feedback.

2.3 Test For EMG Contamination Of EEG Control

To insure that successful loop-closure was due to subject control of EEG and not from control of muscle activity, testing of artifact interaction was performed. The artifact test was conducted with additional electrodes placed to detect possible muscle biopotential (ElectroMyoGram, EMG) contamination of the EEG response sourced from either eye or neck musculature. The amplified EMG signals were compared with the visual evoking stimulation signal. No coherence was found between the evoking stimulus and either of these potential artifact sources. In addition no coherence existed between subjects' EEG and either of the potential artifact sources.

Two subjects showing the greatest degree of EEG narrow band frequency spectrum control from the loop-closure studies were chosen for the artifact study (Subjects 06 and 33, refer to the results section). Utilizing the standard control study procedure, it was established before and after the artifact test that both subjects were able to control their brain wave responses on the day of the artifact test.

3. RESULTS AND DISCUSSION

3.1 SSEP Measurement Results

Describing functions and remnant spectra were obtained from each of the eight subjects tested. Results for the three conditions investigated (evoking stimulus only, evoking stimulus plus easy decision making, and evoking stimulus plus hard decision making) are presented in Figures 3.1 and 3.2. The changes across tasks were specific to each individual tested. As in previous work we classified subjects into two groups: alpha responders, and non-alpha responders. Classification of each subject was based upon alpha band resonance and peak responses for remnant and gain. With task loading, subjects with alpha decreases in both remnant and gain and no changes in beta were classified as alpha responders. Subjects classified as non-alpha responders typically were found to have beta band gain increases with task loading and no alpha band remnant changes (Junker etal., 1987). Results for those subjects classified as alpha responders are plotted in Figure 3.1 and results for non-alpha responders are plotted in Figure 3.2. Each graph includes responses at the sum-of-sines frequencies indicated by circles and triangles. In addition, 'plus or minus one standard error bars' are included. For those cases in which the standard error was less than the height of the graph symbol the error bars were not plotted. Large standard error values indicate that the SSEP response at that frequency was inconsistent and/or weak from trial to trial.

Focusing first on the phase data, during the decision making as compared to the lights only condition, consistent reductions in phase lag in the beta band were observed for all subjects tested (Figures 3.1 and 3.2). Reduction in phase lag in a describing function indicates that a system is producing less lag between the input to the system and the output of the system. Less phase lag can be due to either a decrease in system resonance or to reduced input/output transmission time. Since all the subjects tested exhibited some phase lag reduction with task loading we can conclude that the addition of task loading results in a decrease in resonance or a speeding up of the response of the visual-cortical system. Unfortunately this change in system response was the same whether the easy or hard decision making task was performed. This suggests that the evoked response phase change is an all or nothing phenomenon, and not sensitive to the level of workload experienced.

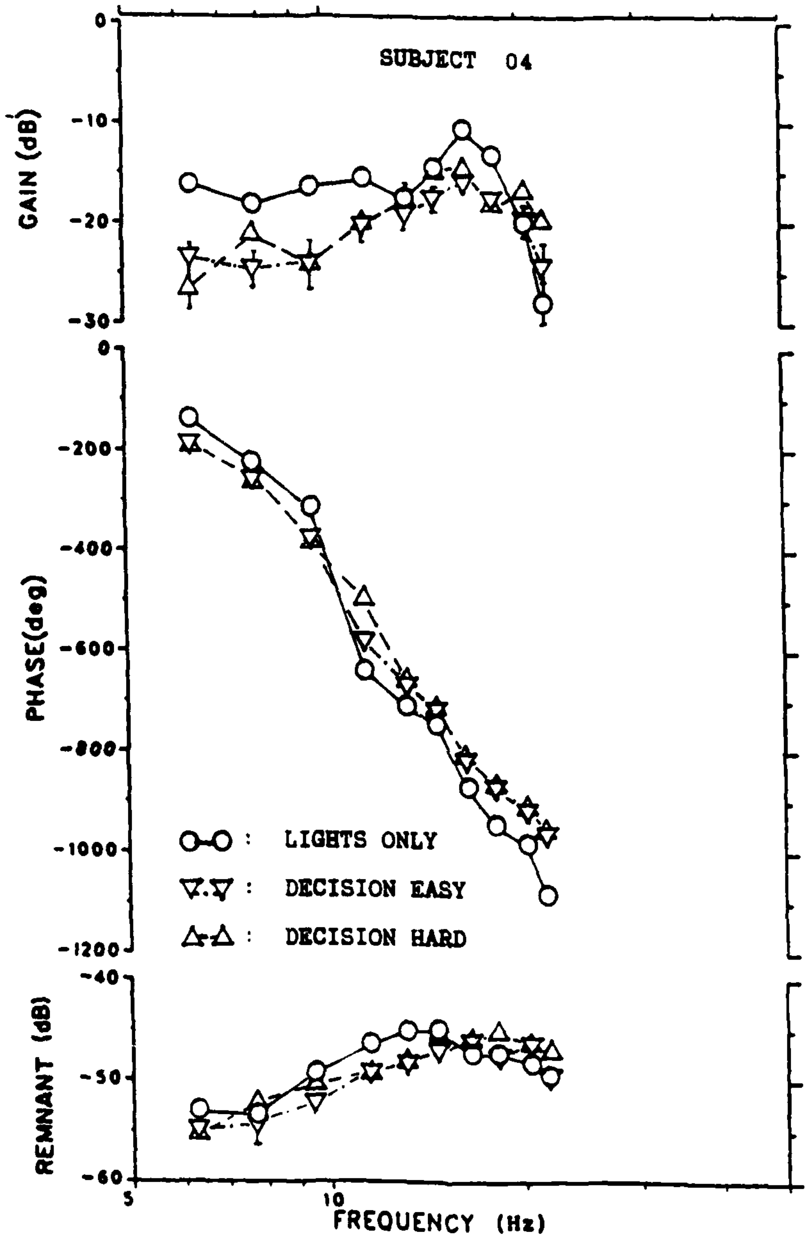


Figure 3.1a. SSEP describing functions and remnant for Subject 04 (alpha responder). Note less phase lag above 9.49 Hz for decision making conditions, and higher gain and remnant values about alpha range (8-12 Hz) for lights only.

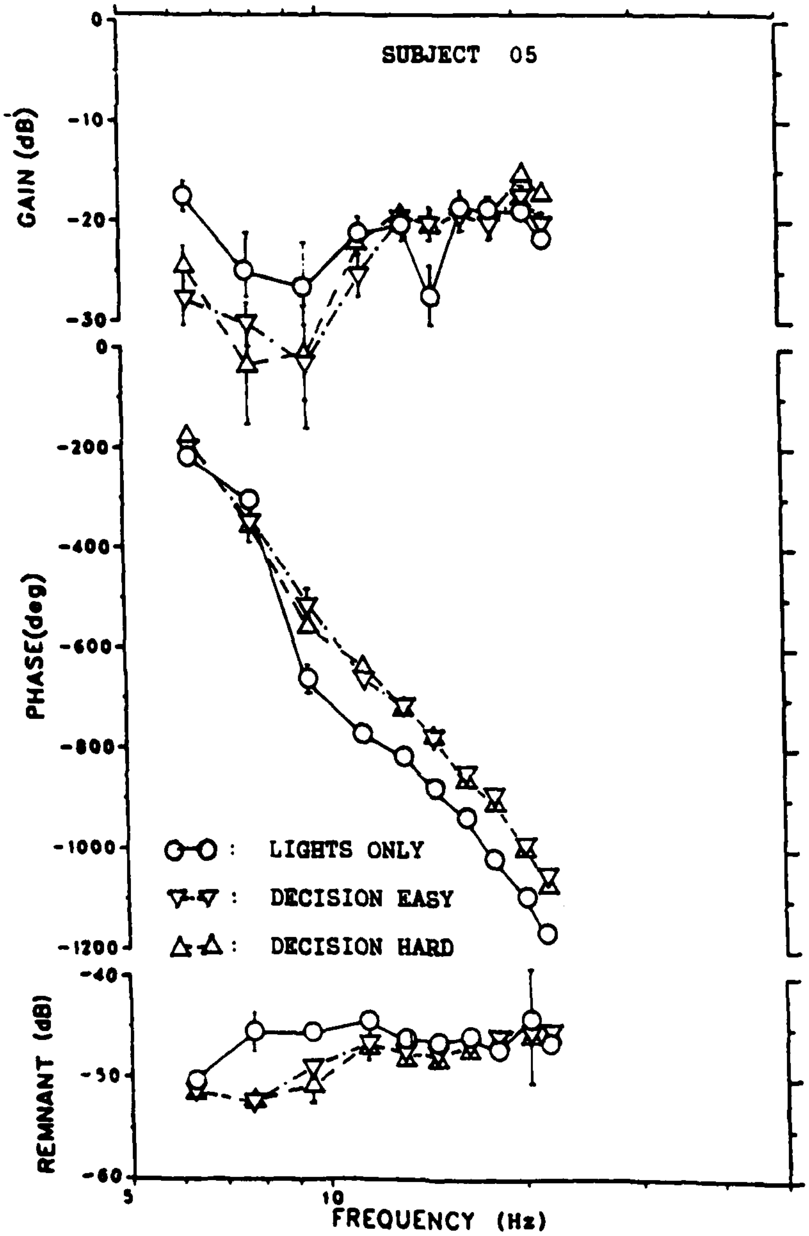


Figure 3.1b. SSEP describing functions and remnant spectra for Subject 05, (alpha responder). Note less phase lag with decision making, and more gain and remnant in alpha band for lights only.

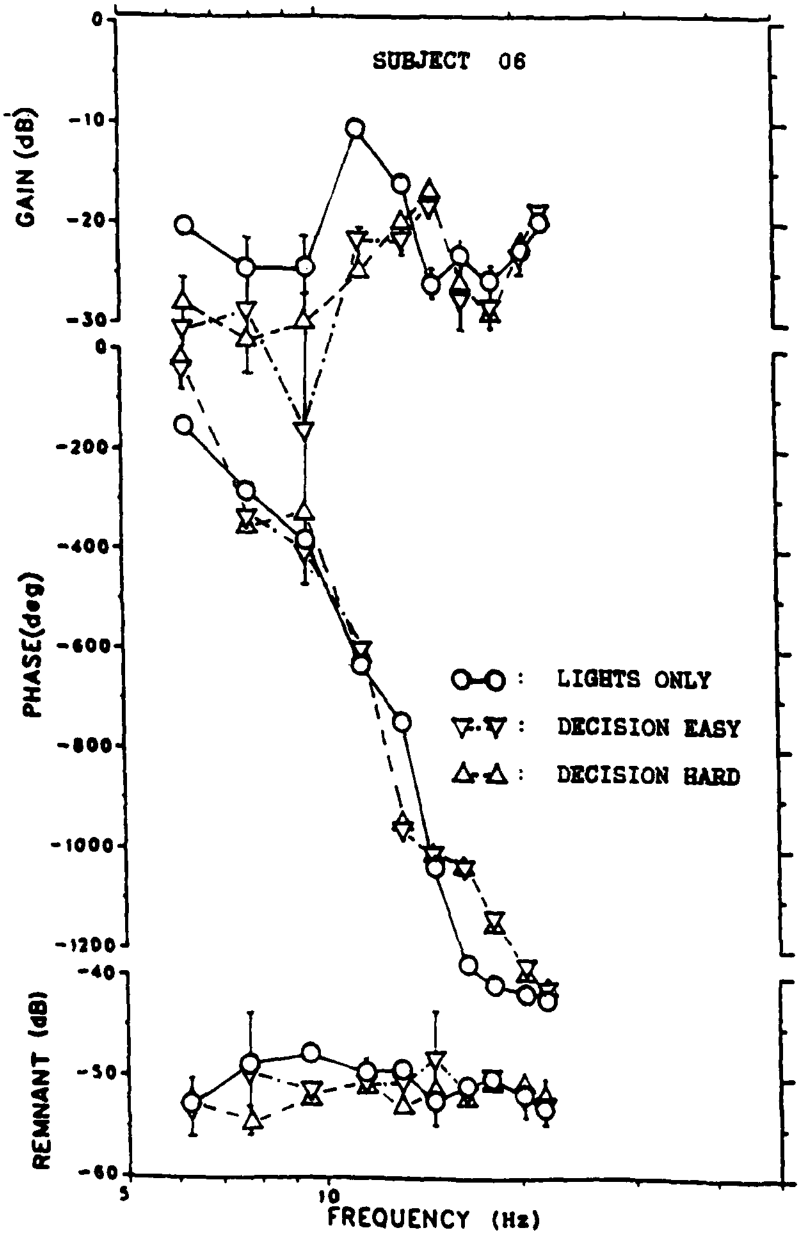


Figure 3.1c. SSEP describing functions and remnant spectra for Subject 06 (alpha responder). Note less phase lag in beta band (above 14.71 Hz) with decision making. Alpha band gain and remnant greater for lights only. Note strong lights only response at 11.49 and 13.25 Hz.

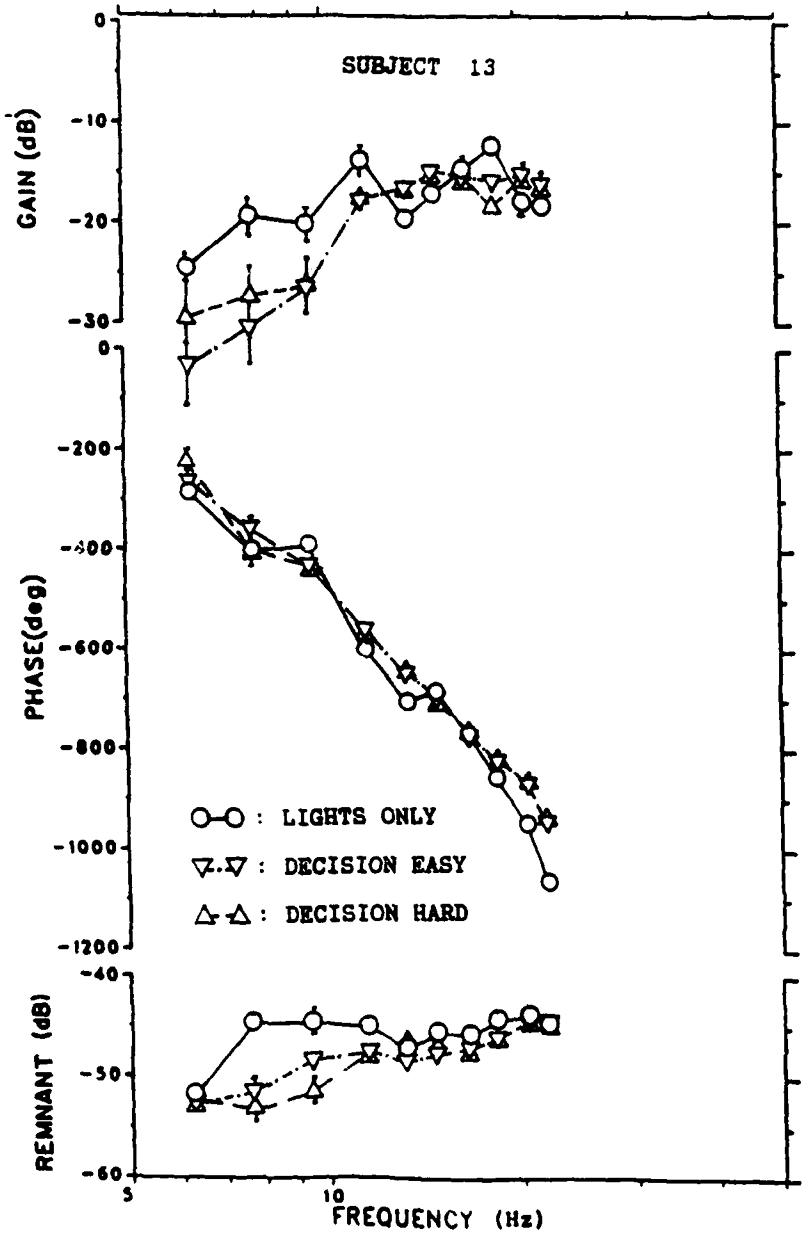


Figure 3.1d. Describing functions and remnant spectra for Subject 13 (alpha responder). Note broad range (7.73 to 11.49 Hz) in which lights only gain and remnant greater.

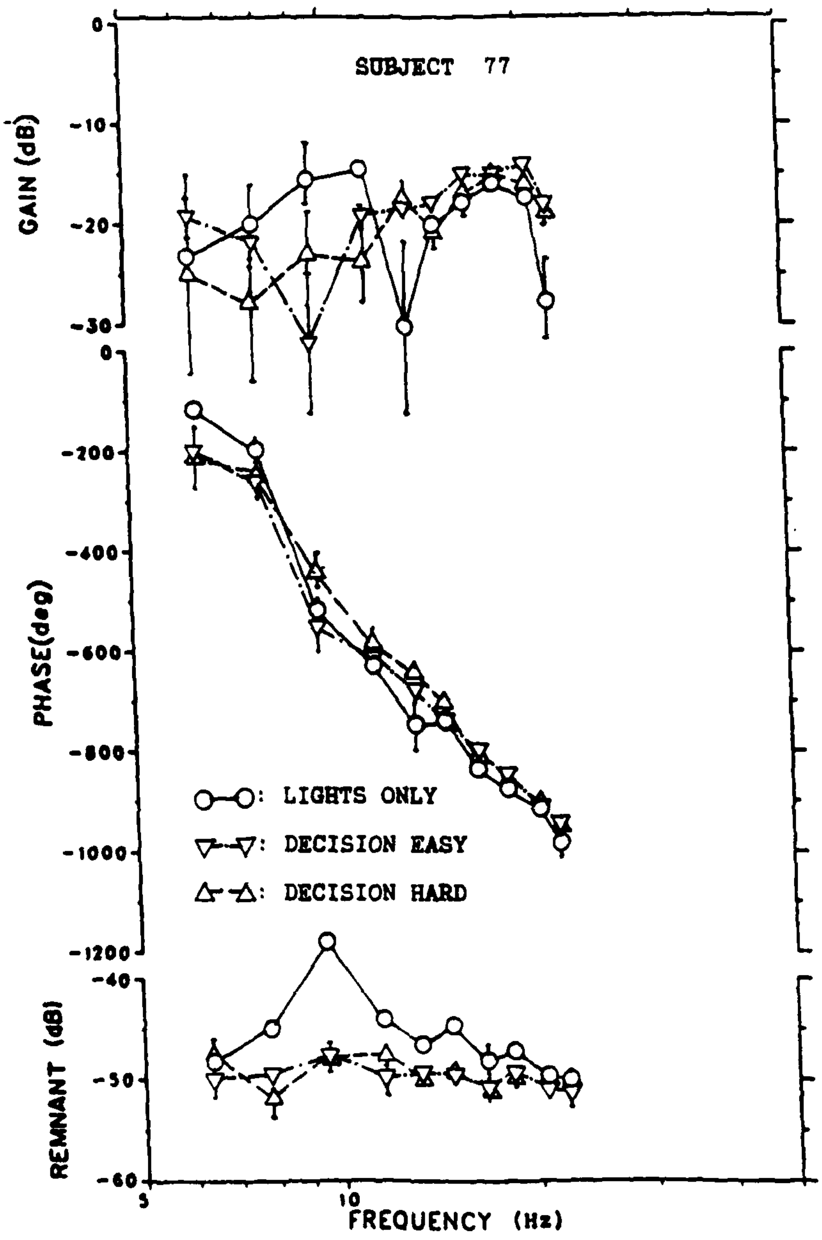


Figure 3.1e. Describing functions and remnant spectra for Subject 77 (alpha responder). Note large lights only alpha peak in remnant spectrum. Note large variability of lights only gain at 13.25 Hz and 7.73 Hz.

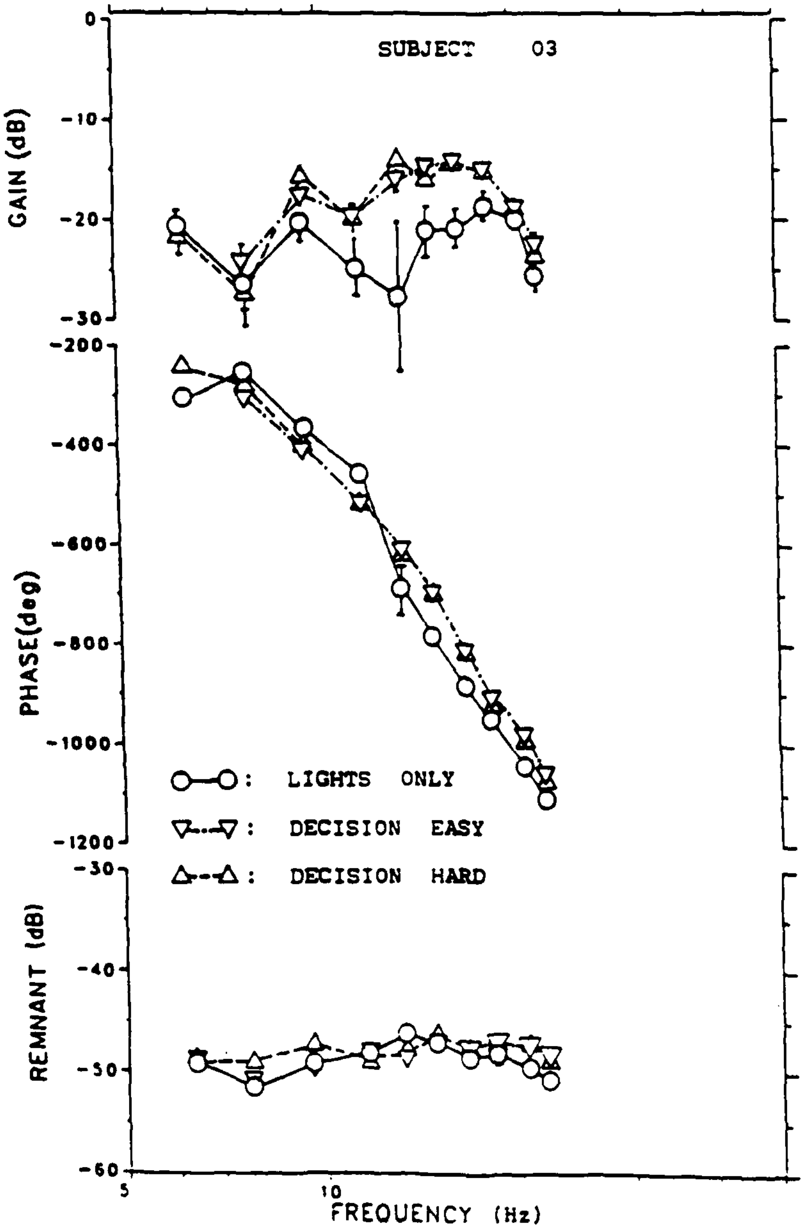


Figure 3.2a. SSEP describing functions and remnant spectra for Subject 03 (non-alpha responder). Note absence of lights only condition peaks in gain and remnant curves. Note large variability of lights only gain and remnant values at 7.73 and 13.25 Hz. Also note less phase lag in beta band (above 11.49 Hz) for decision making conditions.

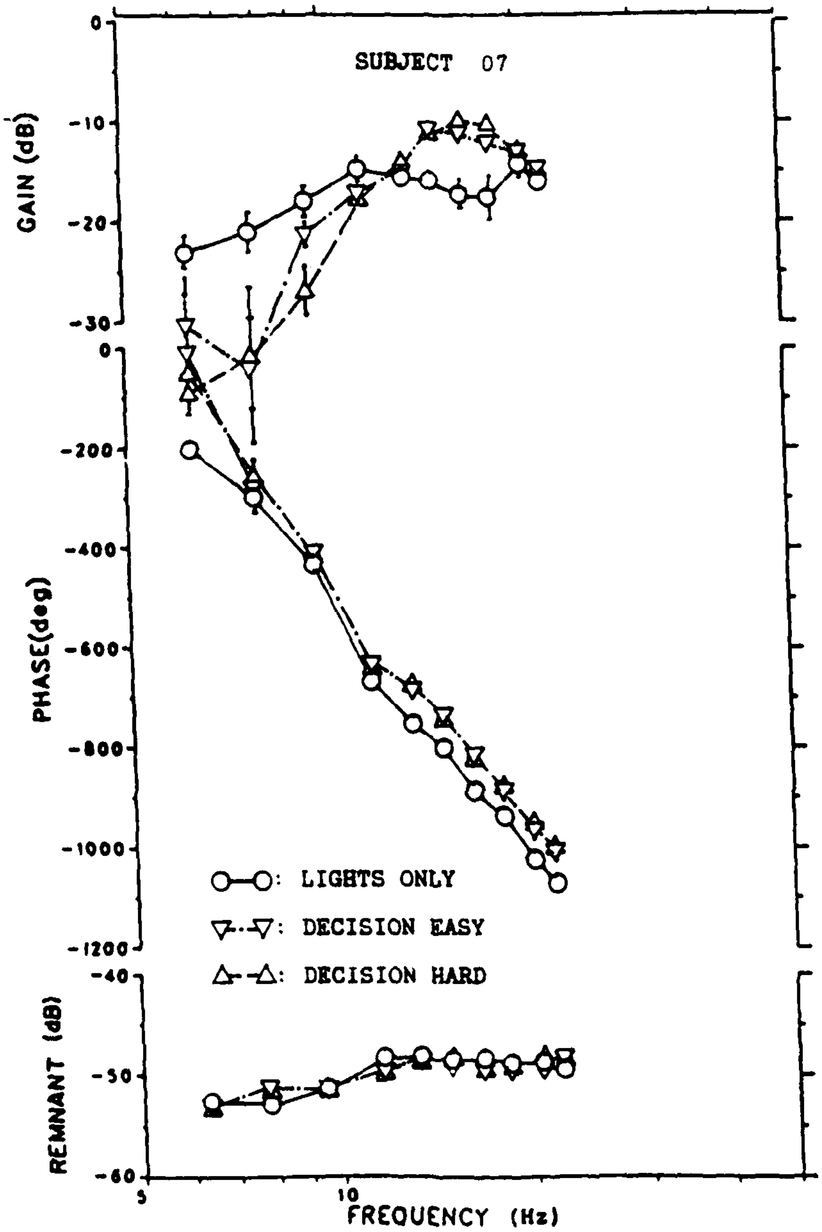


Figure 3.2b. Describing functions and remnant spectra for Subject 07 (non-alpha responder). Note less phase lag in beta band for decision making. Note flat remnant spectra in alpha band. The decrease in alpha band gain and increase in beta band gain with task loading is a mixture of alpha and non-alpha responder characteristics.

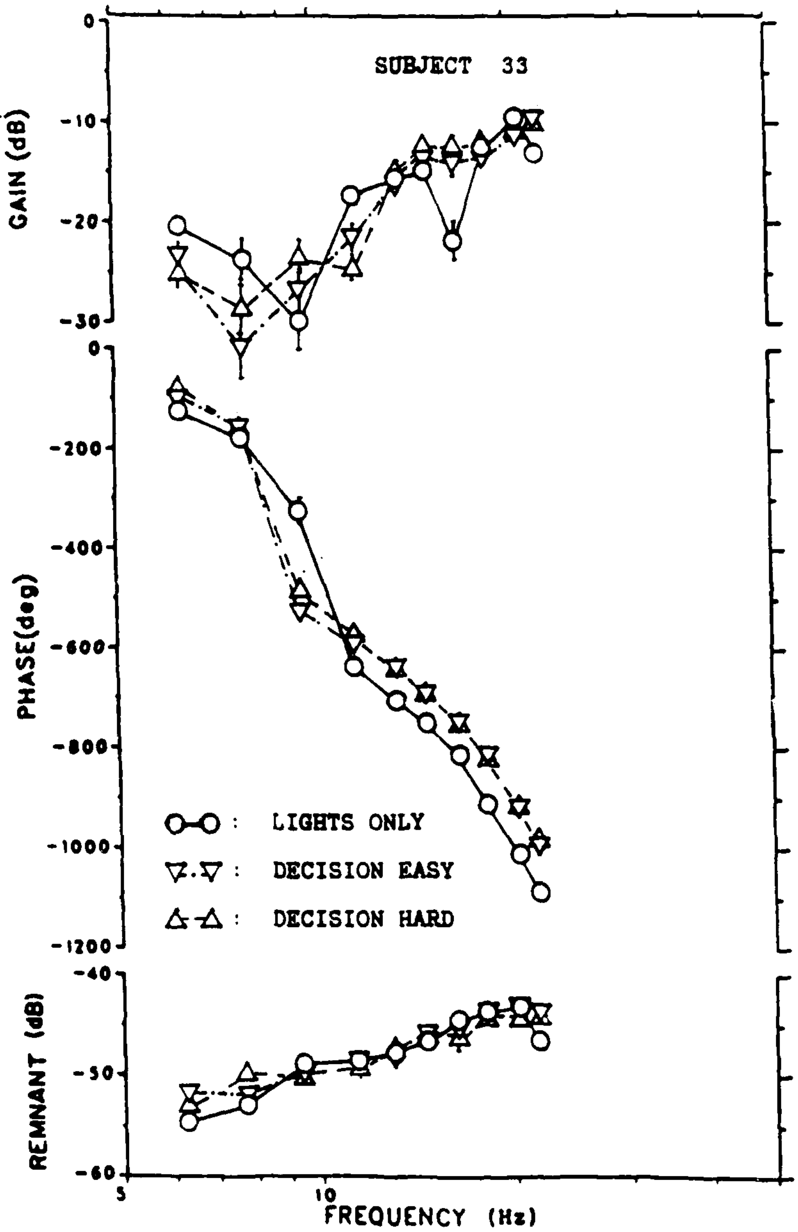


Figure 3.2c. Describing functions and remnant spectra for Subject 33 (non-alpha responder). Note little change in remnant spectra across conditions. Also note variability of lights only gain at 7.73 and 13.25 Hz and less phase lag in beta band for decision making.

Turning next to the gain and remnant data, decreases in alpha band gain and remnant under task loading were observed for the subjects classified as alpha responders (Figure 3.1). These observed decreases in the gain and remnant curves can be interpreted as reductions in resonance of the alpha responders. An opposite trend was observed for those subjects classified as non-alpha responders, namely increases in gain in the beta band and no changes in the remnant spectra with task loading (Figure 3.2). The increase in beta band gain for the non-alpha responders suggests that more beta activity occurred with task loading than without. This is a somewhat opposite trend to that observed for the alpha responders who exhibited decreases in their gain in the alpha band but no change in their gain in the beta band. An increase in beta activity is often associated with an increase in focused mental activity. To achieve this increase alpha responders may perhaps decrease their alpha activity, while non-alpha responders increase beta activity to achieve the same result. As with the phase data, it must also be pointed out that differences in evoked response gain and remnant across the two levels of decision making were not observed for any of the subjects tested.

As part of the two decision making tasks, scores of average decision making task performance were computed. These scores are presented for the eight subjects tested in Table 3.1. Subjects were grouped according to their alpha or non-alpha classification. Performance scores are given as percent of tasks completed. A higher score indicates that more tasks were completed and represents better performance. Included in the table are sex and responder type for each subject. No consistent patterns were observed, as can be seen in Table 3.1. From these results it would appear that task performance is independent of sex or responder type.

Table 3.1 Decision making performance scores

		% TASKS COMPLETED				
		"EASY" COND.		"HARD" COND.		RESPONDER
SUBJ#	SEX	MEAN	SD	MEAN	SD	TYPE
04	F	82.4	1.8	30.2	5.9	ALPHA
05	M	80.5	4.8	36.2	3.2	ALPHA
06	F	72.4	6.2	36.0	7.1	ALPHA
13	M	75.4	3.0	38.2	6.8	ALPHA
77	F	76.5	2.4	33.5	3.0	ALPHA
03	M	79.1	4.0	41.9	6.1	NON-A
07	M	69.0	9.9	27.3	4.8	NON-A
33	F	84.5	1.3	31.9	6.4	NON-A

Based upon the above results we would conclude that SSEP measurements, as obtained in this report, are not sensitive to levels of task loading and would therefore not be useful as indicators of subject performance or workload. As stated in the introduction, these SSEP measures are open-loop suggesting that there would not exist a systematic variation of open-loop SSEPs with changes in levels of task loading. This suggestion is supported by the data. There was a consistent all or nothing change between no tasks and tasks, but no consistent change between levels of task loading.

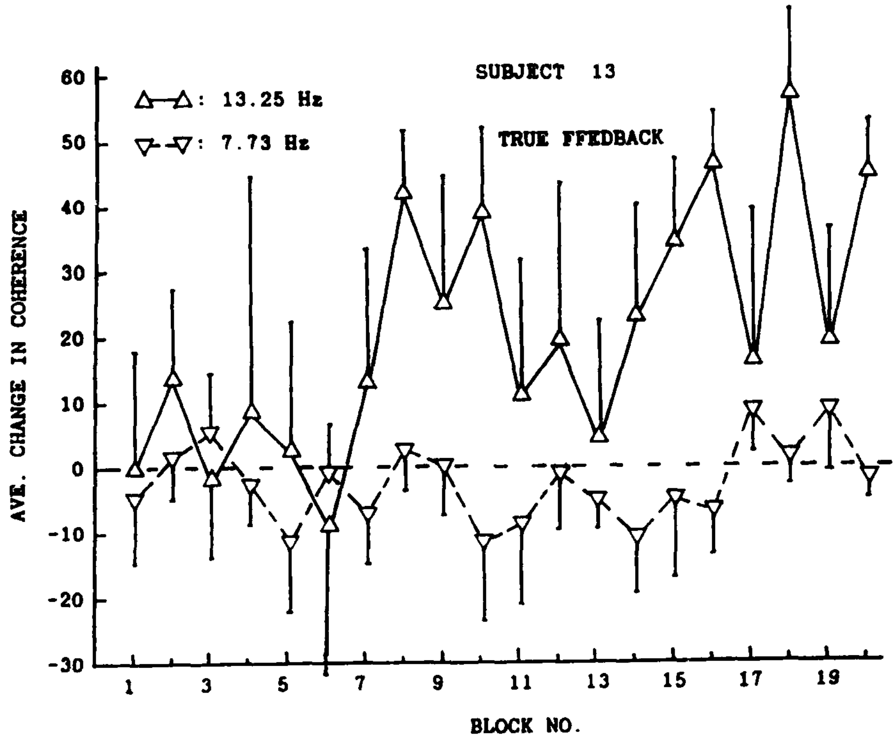
3.2 Feedback Training Results: True Feedback Versus False Feedback

Four subjects were used to evaluate the effectiveness of providing true feedback versus false feedback as an aid to learning EEG resonance control. As stated in Section 2.2, Subjects 13 and 07 received true feedback and Subjects 77 and 03 received false feedback.

Before beginning discussion of the true versus false feedback training results it is informative to refer back to the four Subjects' describing functions and remnant spectra in Figures 3.1 and 3.2. Looking at Subject 13's responses, a weak and inconsistent gain response at the lower frequency (7.73 Hz) as indicated by the large standard error bars for the three conditions tested can be observed. The response at 13.25 Hz for the lights only condition was low but increased with task loading. Subject 77's responses at both frequencies were low and highly variable as indicated by the mean values and the large standard error bars. Subject 07 exhibited large variability in the evoked response at 7.73 Hz. Subject 03's response at 13.25 Hz for the lights only condition was weak. Ways in which these values relate to loop-closure will be considered next.

Loop-closure performance as indicated by coherence and average time above threshold are plotted for the four subjects in Figures 3.3 and 3.4. Plotted in each graph are the average values and the largest standard deviation (either from increasing or suppressing) per block. A value above the dashed line in each graph indicates for that block the average of the 4 'increasing' values was greater than the average of the 4 'suppressing' values. Values below the dashed line indicate that the opposite trend occurred.

The coherence results for Subject 13 at 7.73 Hz (Figure 3.3a) indicate that no net change in coherence occurred due to feedback training. Over the 20 blocks, the average value in coherence was only slightly greater when suppressing than when increasing. At 13.25 Hz, however, by the seventh block an evident increase in coherence difference between the



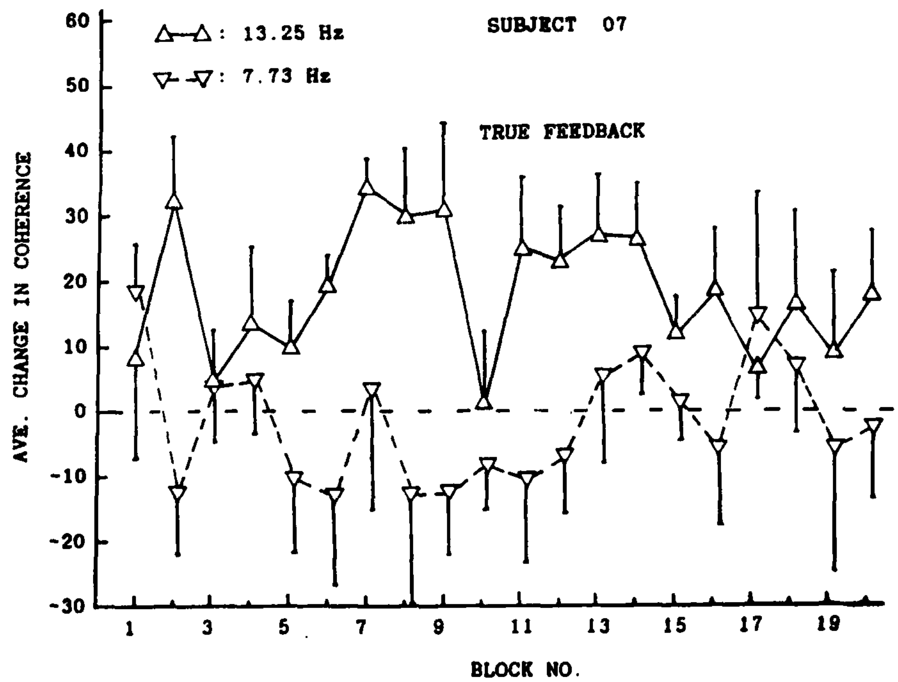
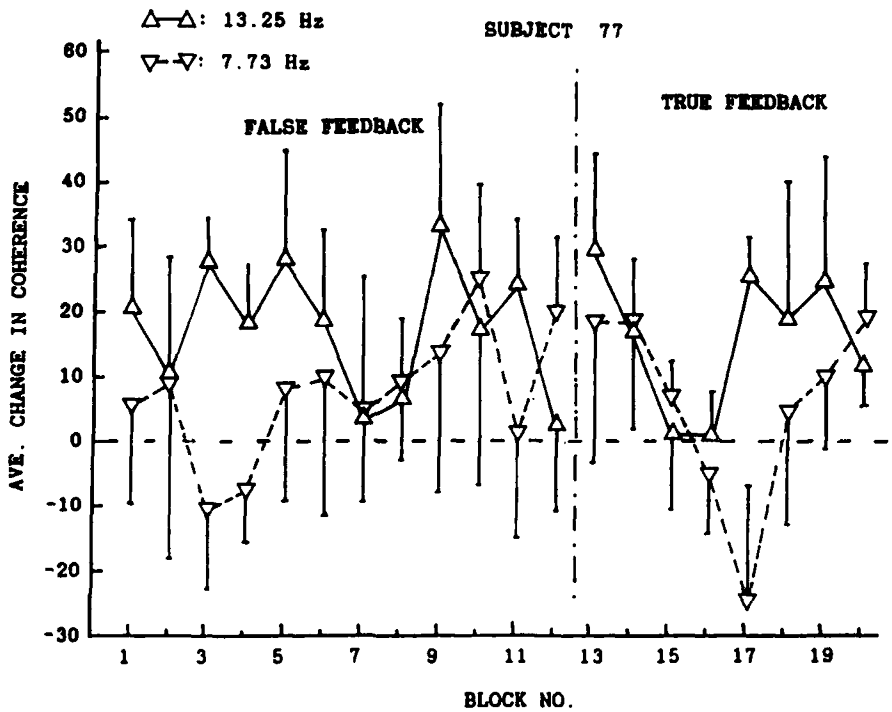


Figure 3.3a. Average change in coherence for subjects with true feedback, standard deviation bars included.



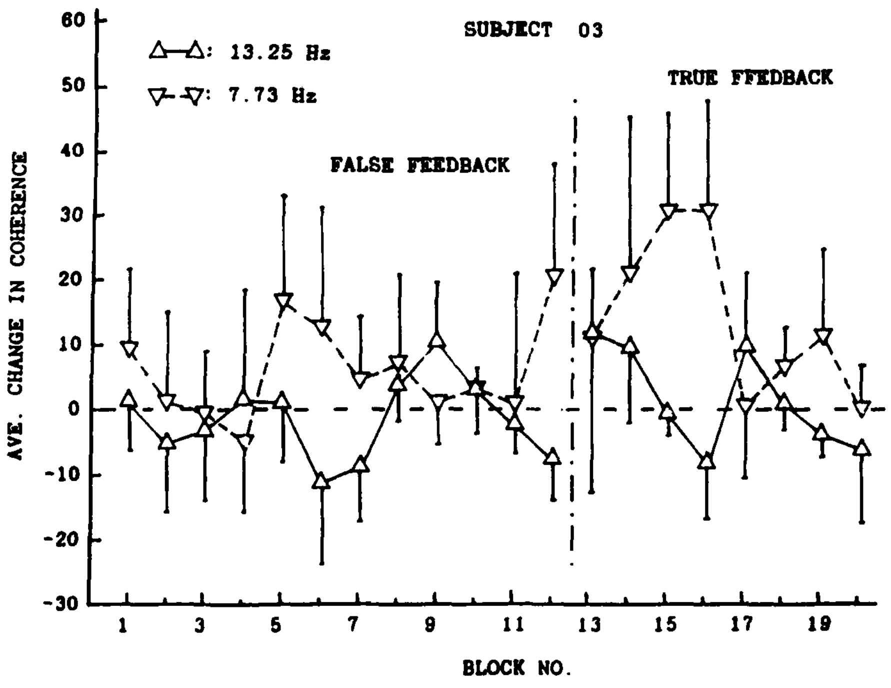
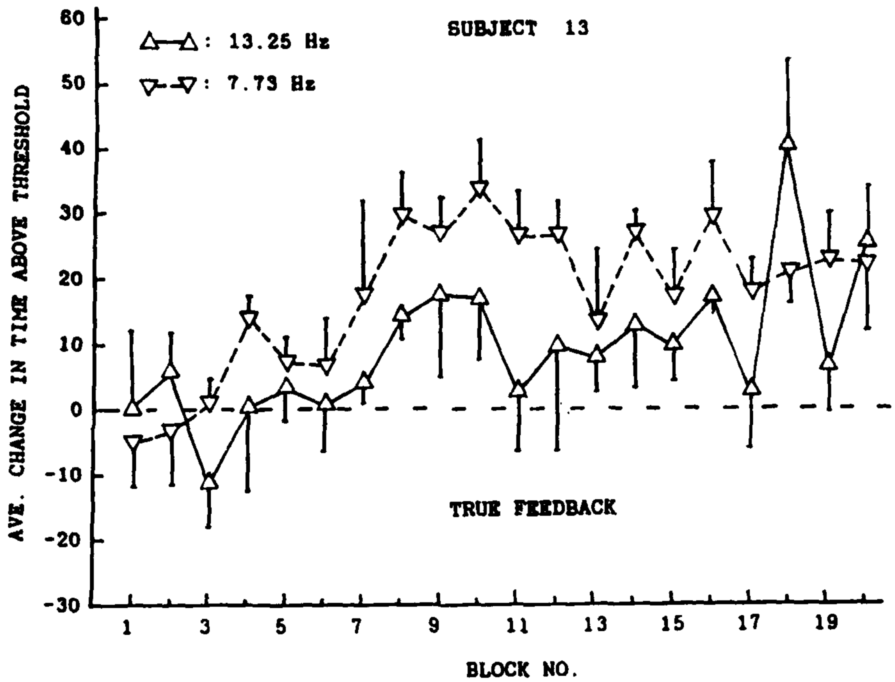


Figure 3.3b. Average change in coherence for subjects who received false feedback for the first 12 trials, and true feedback for 8 subsequent trials.



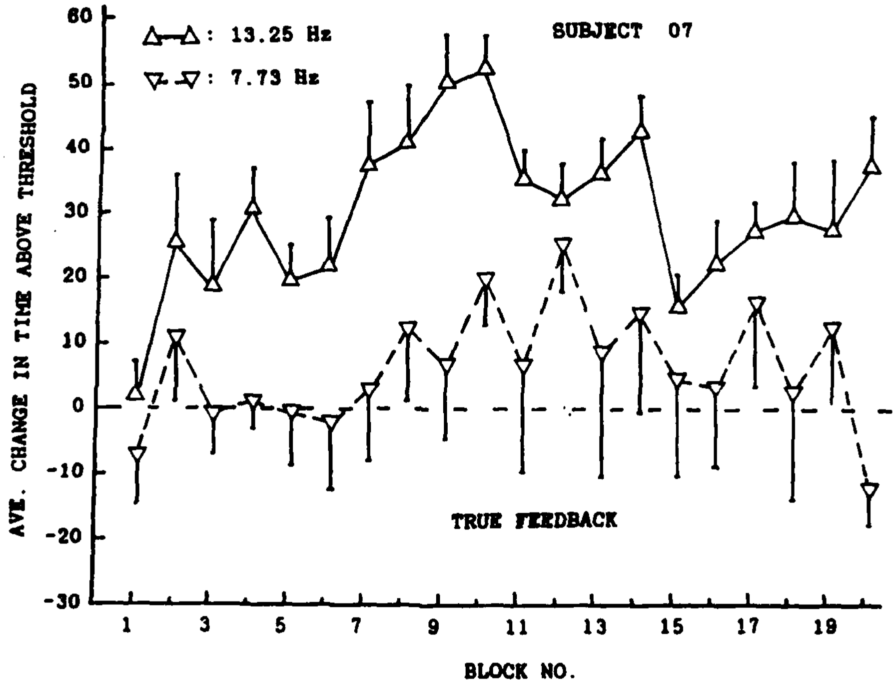
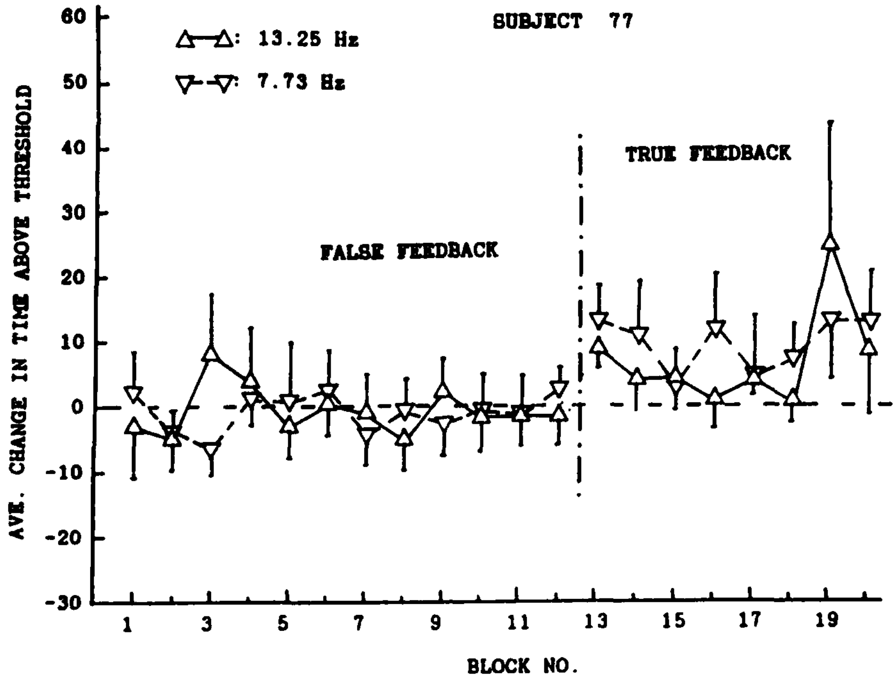


Figure 3.4a. Average change in 'time above threshold' for subjects who received true feedback. Positive values indicate longer time above threshold for increasing trials than for suppressing trials.



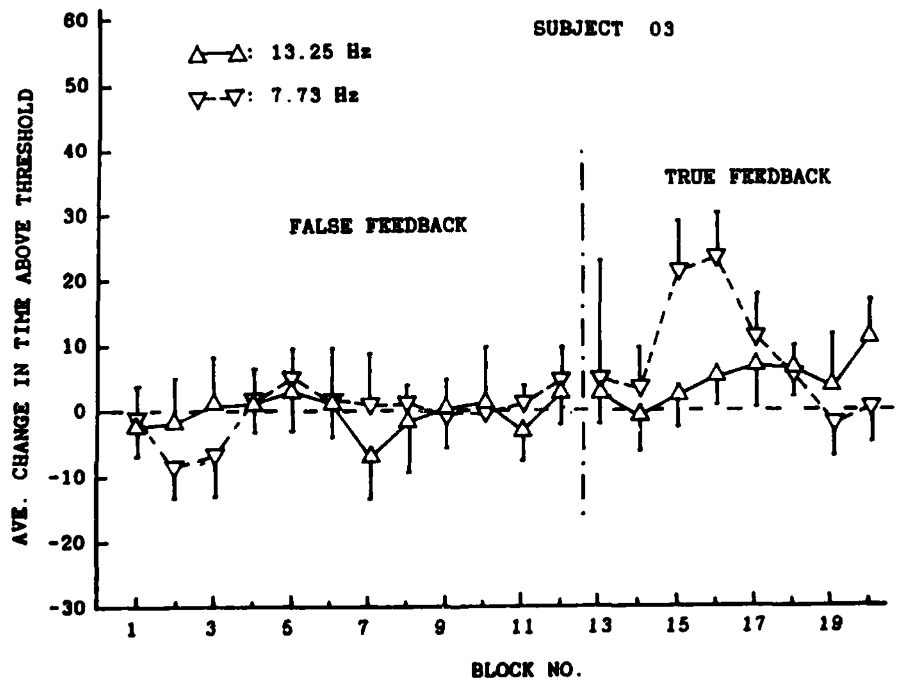


Figure 3.4b. Average change in 'time above threshold' scores for subjects receiving false feedback for 12 trials, and then true feedback for 8 trials.

increasing and suppressing trials can be observed. The lack of change in coherence at 7.73 Hz may relate to the weak response obtained in the Subject's describing functions of Figure 3.1. Subject 07 exhibited trends similar to Subject 13 in both the average change in coherence and in the describing functions of Figure 3.2.

Data for the subjects receiving false feedback for 12 blocks and then true feedback for 8 blocks are shown in the second two graphs of Figure 3.3. Subject 77 exhibited greater average coherence during the increasing trials for 13.25 Hz, even during the false feedback conditions. Due to the large variation in the data however this trend was not consistent. Subject 03 exhibited greater coherence during the increase trials as compared to the suppress trials with both true and false feedback at 7.73 Hz, but not at 13.25 Hz. This corresponds to the gain sensitivity observed for Subject 03 in Figure 3.2. Neither subject exhibited strongly consistent trends in coherence difference during the eight trials of true feedback. For the true feedback group, consistent positive trends in coherence were exhibited by subjects after 7 blocks. Since the false feedback group had only 8 blocks of true feedback training for this phase of the experiment, it is reasonable that no significant trends in coherence were observed.

In contrast to Subject 13's coherence change previously discussed, this Subject's positive average change in time above threshold (Figure 3.4a) was consistently higher for 7.73 Hz than for 13.25 Hz. Note that it was not until the 8th block that consistent control began to be evident. Blocks 18 and 20 indicate that a big step in learning at 13.25 Hz had occurred. Subject 07 exhibited strong consistent control at 13.25 Hz and marginal control at 7.73 Hz beginning with block 2.

For the second group, during false feedback, the average time above threshold was approximately zero as it was a result of the LAS processing noise. The plots for Subjects 77 and 03 during false feedback are actually plots of what they saw and heard in terms of feedback cues and not actual EEG signals. Time above threshold computations of actual EEG would have required a second LAS which was not available. When given true feedback both subjects began to exhibit positive average times above threshold indicating EEG control. Improvements similar to those observed for Subjects 13 and 07 were expected with further sessions. This, in fact, was the case, especially for Subject 13 (discussed in Section 3.4).

3.3 Spectral Measurements of Loop-Closure Effects

Presented in Figure 3.5 are graphic illustrations of the results of subjects consciously controlling their EEG potentials with the aid of feedback as provided by the apparatus utilized in this report. Spectral plots were obtained from Subjects 07 and 13 by using the HP model 3582A Spectrum Analyzer. These average spectral plots were for 100 second trials of either raising or lowering the feedback response at the 13.25 Hz control frequency. Note the distinct presence of a peak response at 13.25 Hz for the raise trials and the absence of this peak for the lower trials. Also note the different overall spectral shapes between the alpha producer (Subject 13) and the non-alpha producer (Subject 07). Control at 13.25 Hz is independent of the absence or presence of an alpha resonance. This is not the case at 7.73 Hz as will be discussed in the next section.

3.4 True Feedback Training Results

Results from the two subjects who received false and then true feedback (Subjects 03 and 77) and results from the four subjects not used in the first loop-closure tests (Subjects 04, 05, 06, and 33) are considered in this section. Data are grouped by subject and plotted in Figure 3.6a through 3.6f.

The results of the last 12 sessions of training with true feedback for Subject 03 are presented in Figure 3.6a. Average time above threshold and average coherence are presented together. From the graphs it can be seen that this subject exhibited control at 7.73 Hz, as indicated by the mean values lying above the zero line. However, this control was inconsistent. Little control was accomplished at 13.25 Hz. Referring back to the SSEP results of Figure 3.2, this subject, classified as a non-alpha responder, had a weak response at 13.25 Hz. As with other subjects there appears to be a relationship between this subject's SSEP and his ability to achieve loop-closure.

The other subject to get false and then true feedback, Subject 77, is considered next (Figure 3.6b). Unlike Subject 03, Subject 77 exhibited control at 13.25 Hz with corresponding changes in coherence. Little control was accomplished at 7.73 Hz as indicated by the data. Going back to the SSEP plots for this subject (Figure 3.1) we note that Subject 77 was classified as an alpha responder. In addition this subject's alpha band, as indicated by the 'lights only' remnant spectrum, appears to span a wide frequency range, overlapping the 7.73 Hz loop-closure frequency. This subject is considered to exhibit broad band alpha. By broad band is meant that the remnant values for the lights only condition

SUBJECT 13

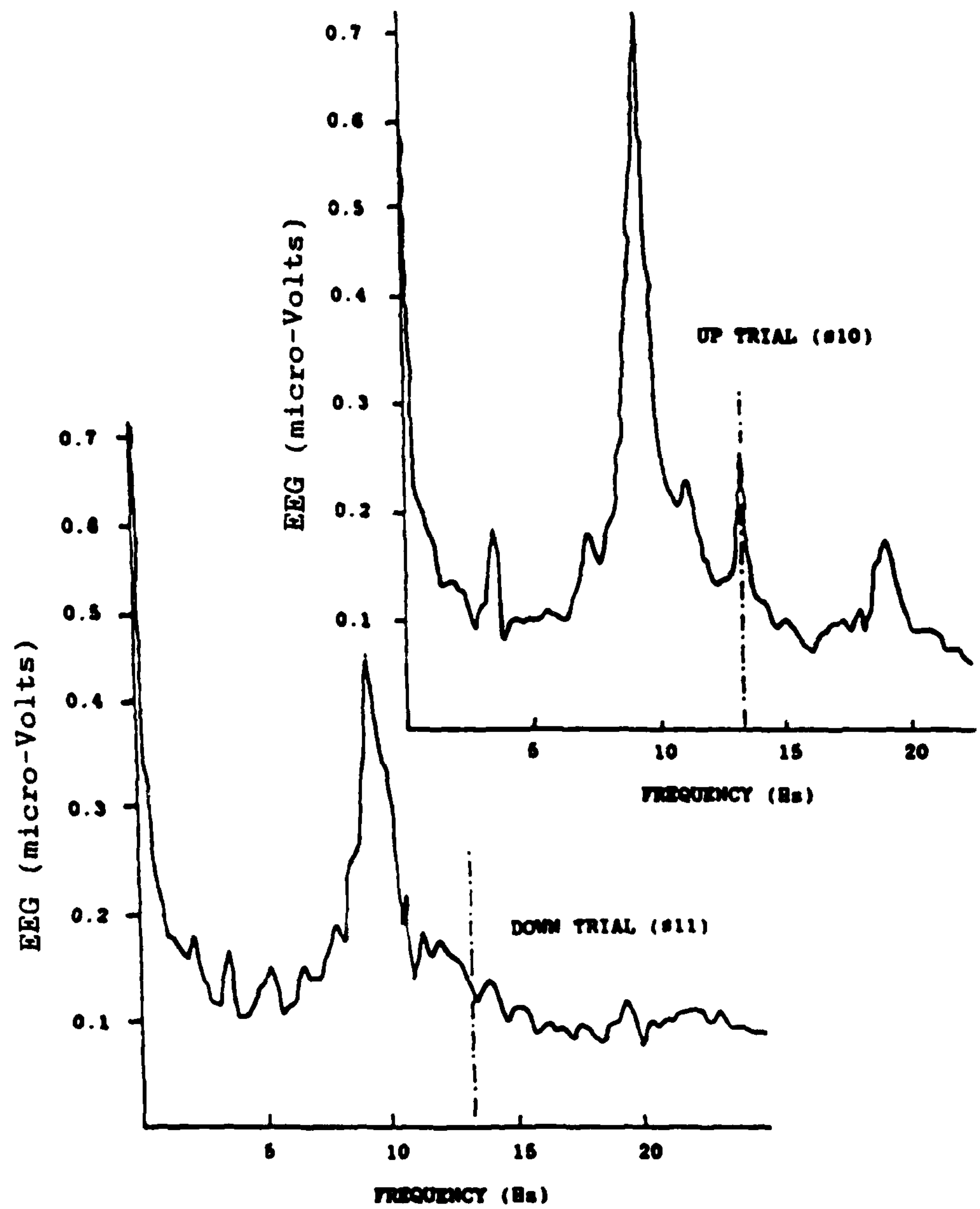


Figure 3.5a. Effects of conscious EEG increase and suppression at 13.25 Hz for Subject 13.

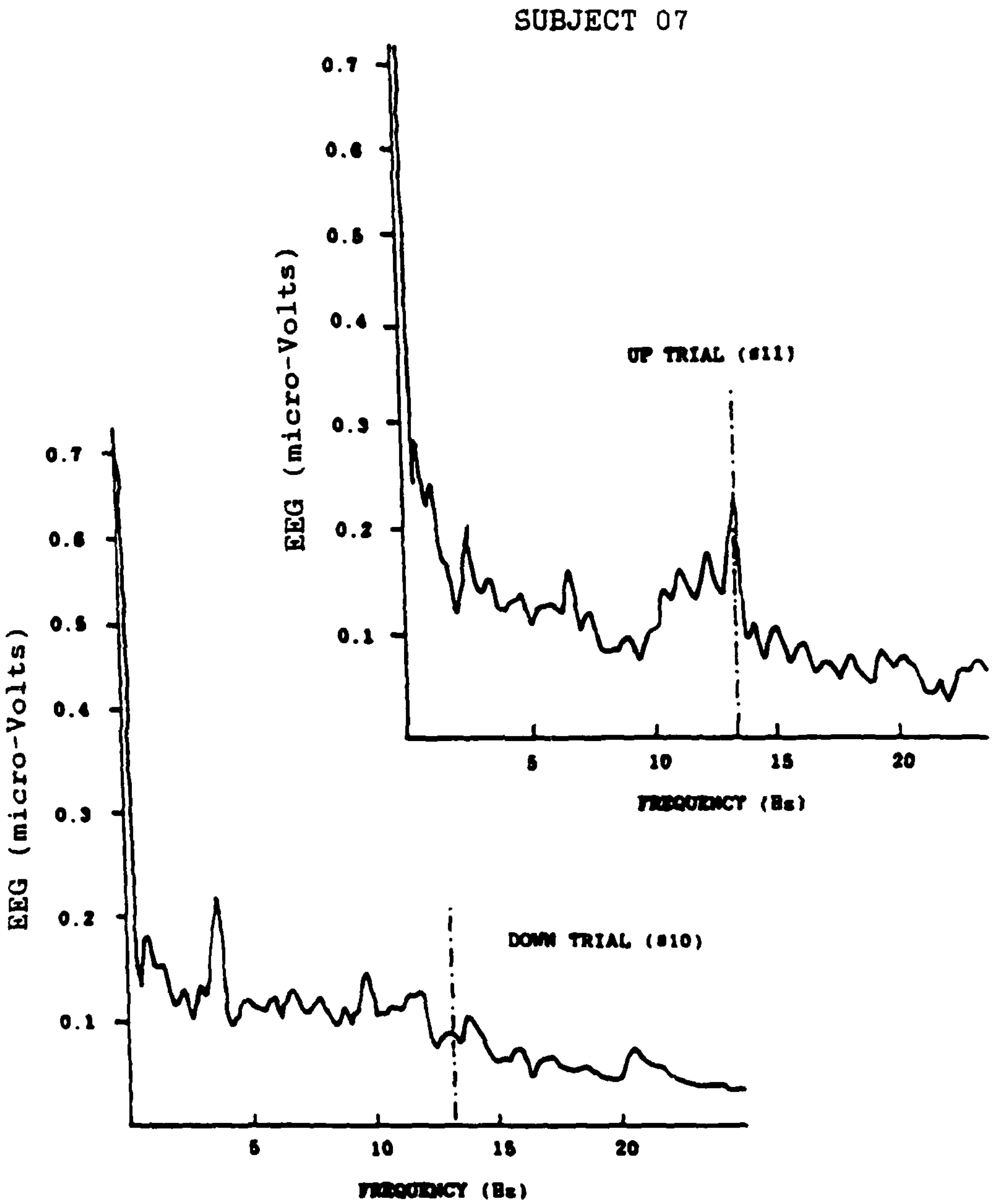
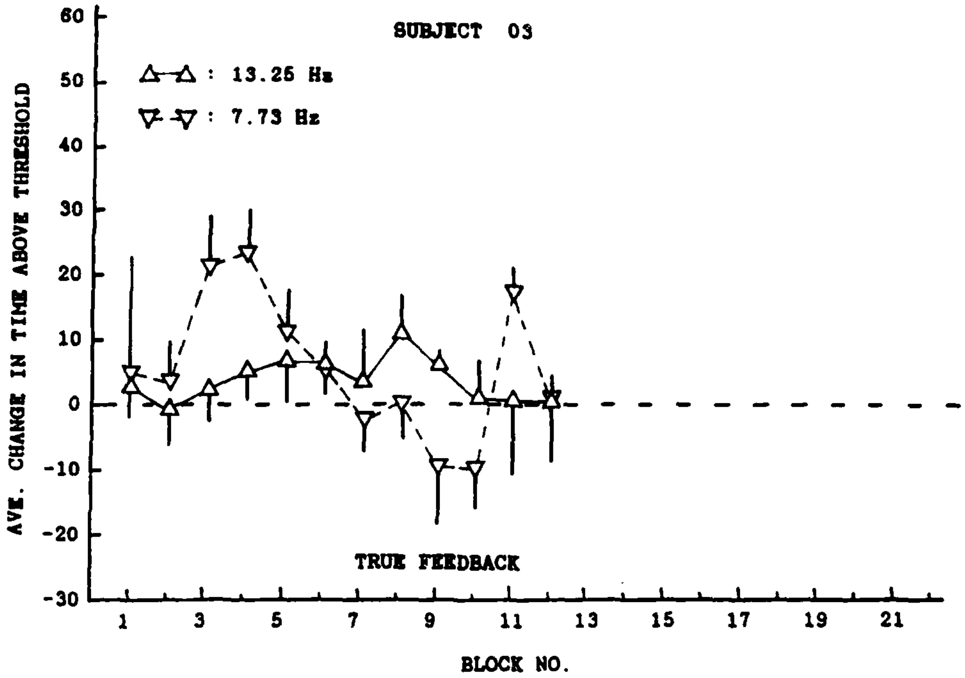


Figure 3.5b. Effects of conscious EEG increase and suppression at 13.25 Hz for Subject 07.



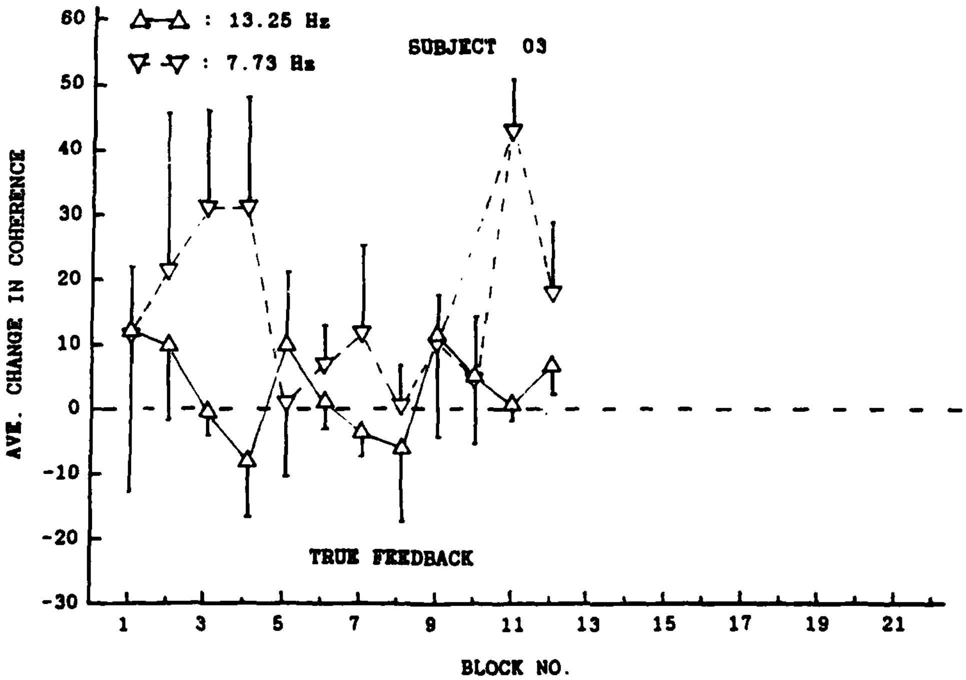
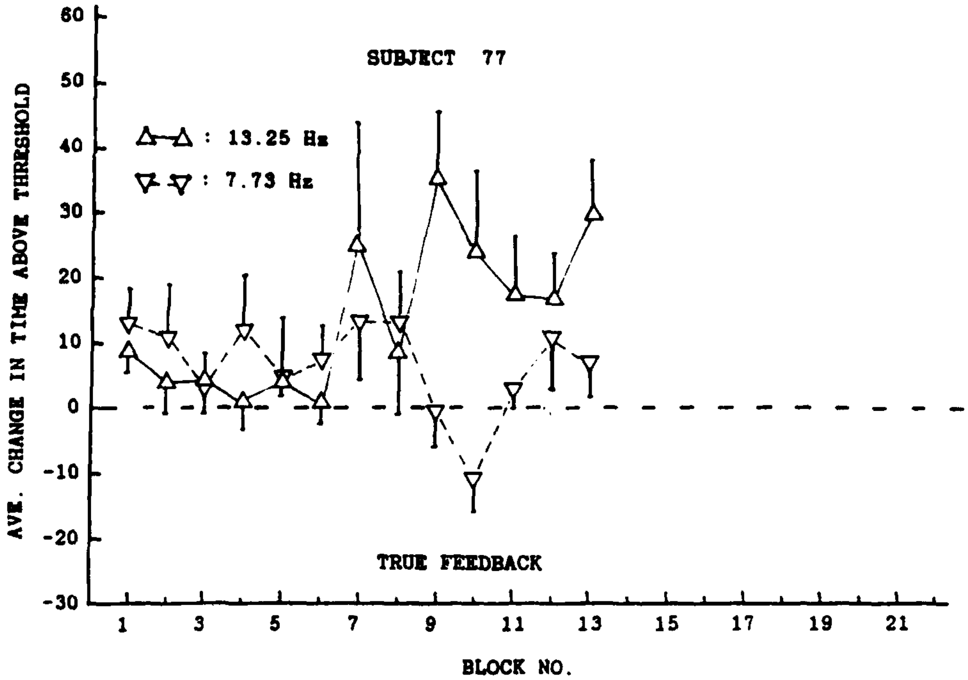


Figure 3.6a. Twelve sessions of training with true feedback for Subject 03 (block 1 refers to block 13 of Figure 3.3b). Note little control at 13.25 Hz and erratic control at 7.73 Hz indicated by mean values above dashed line.



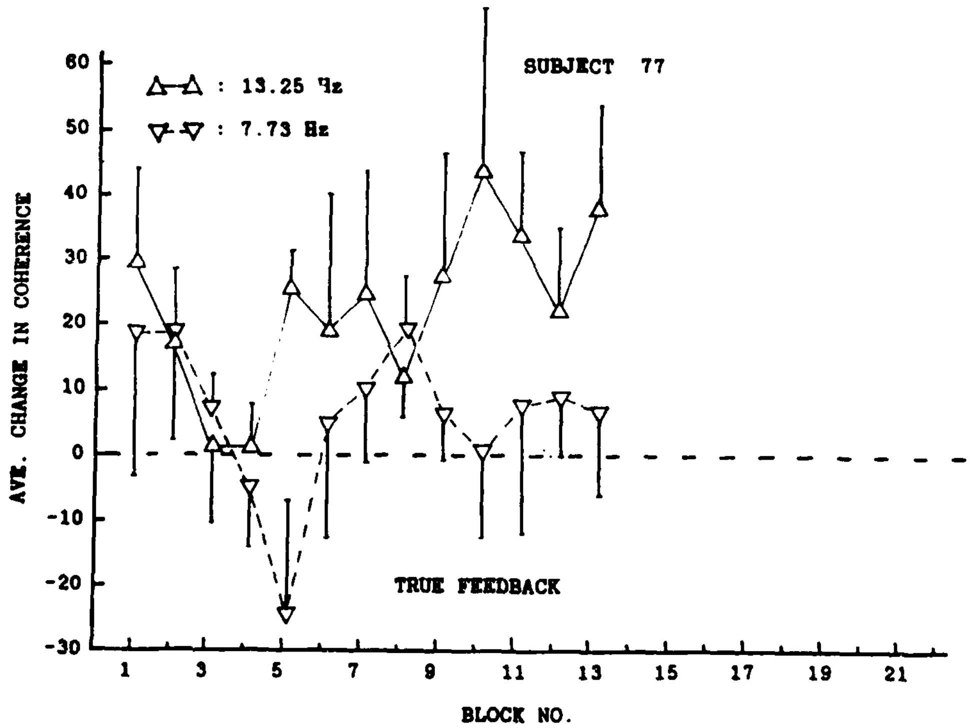
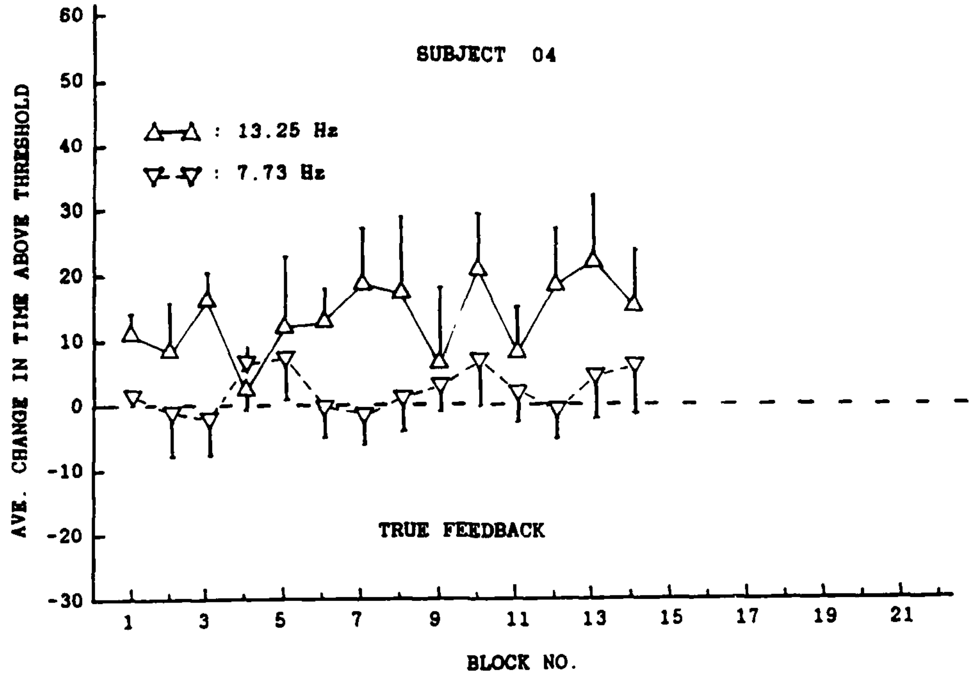


Figure 3.6b. Thirteen consecutive sessions of true feedback after false feedback training, for Subject 77. Consistent control at 13.25 Hz after 8th block.



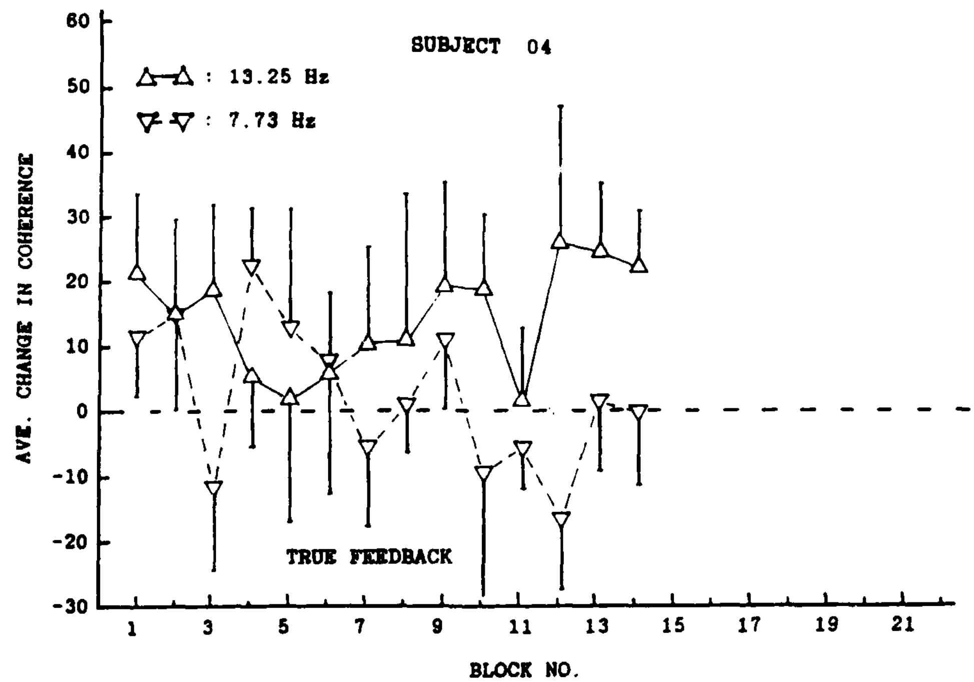
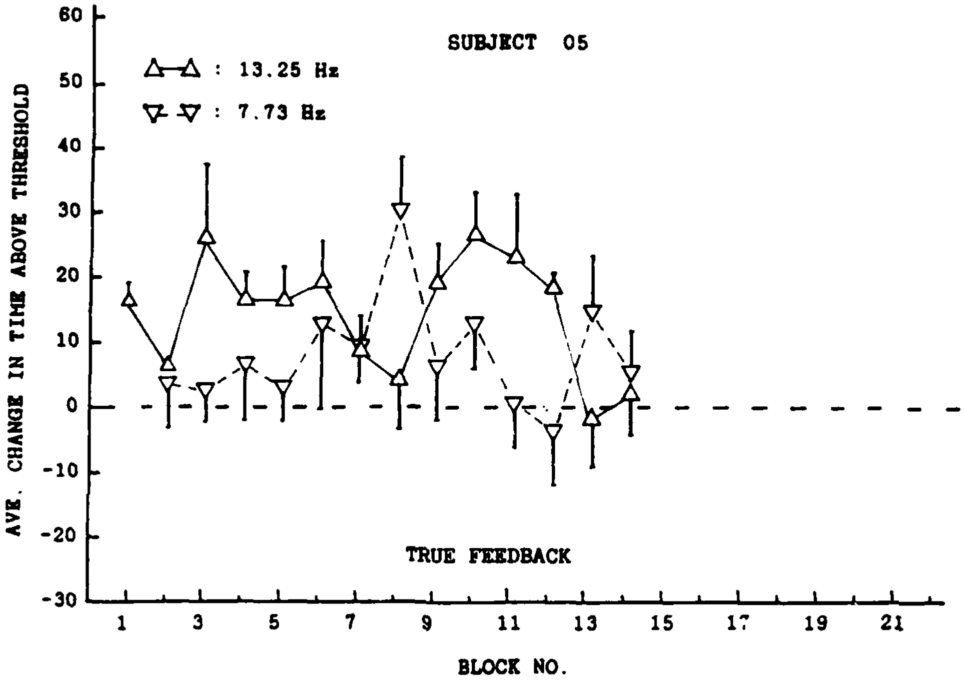


Figure 3.6c. Average change in time above threshold and change in coherence for Subject 04. Note conscious control at 13.25 Hz, little control at 7.73 Hz.



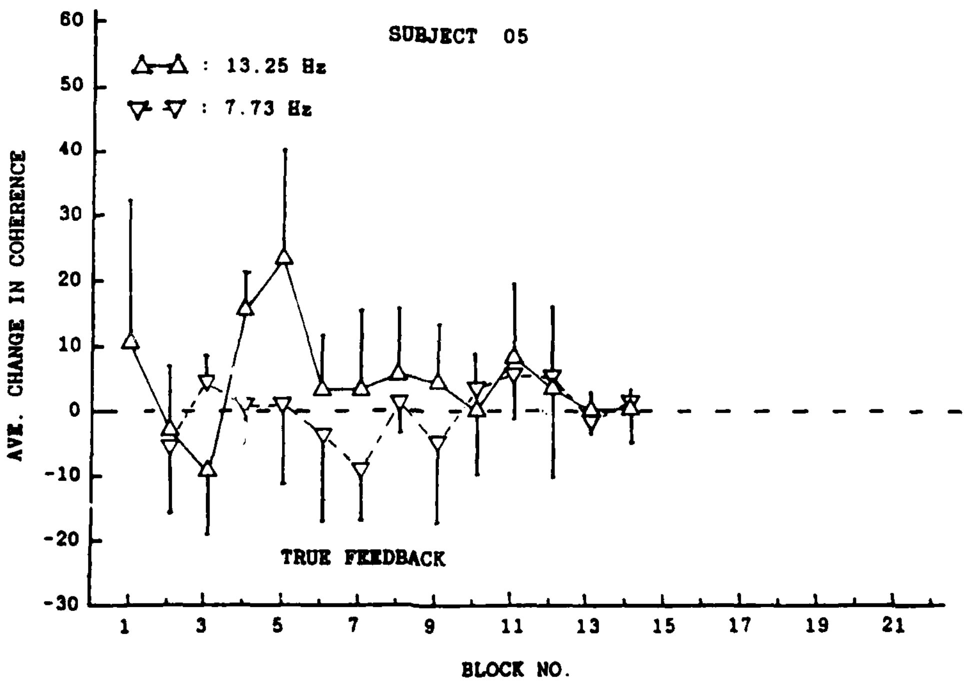
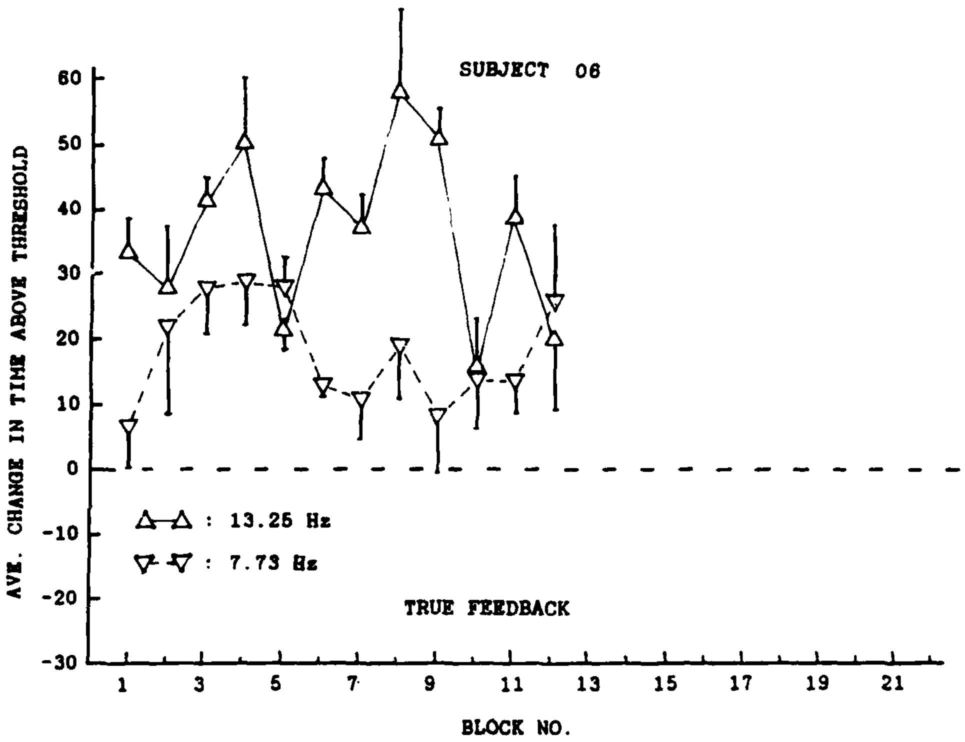


Figure 3.6d. Results for Subject 05. Note more consistent control at 13.25 Hz, little average change in coherence between raise and lower conditions.



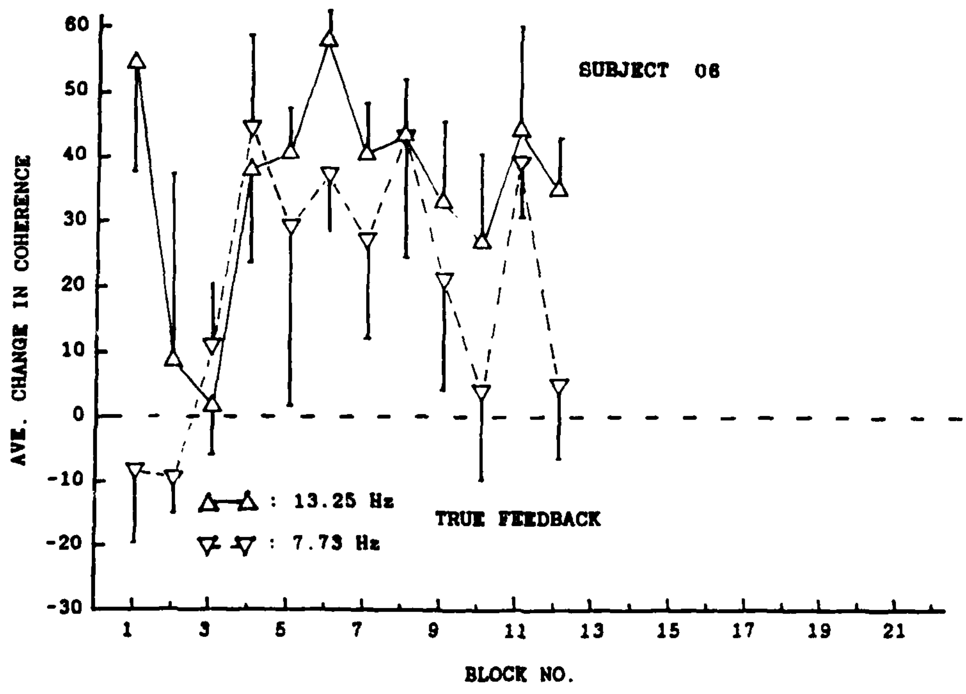
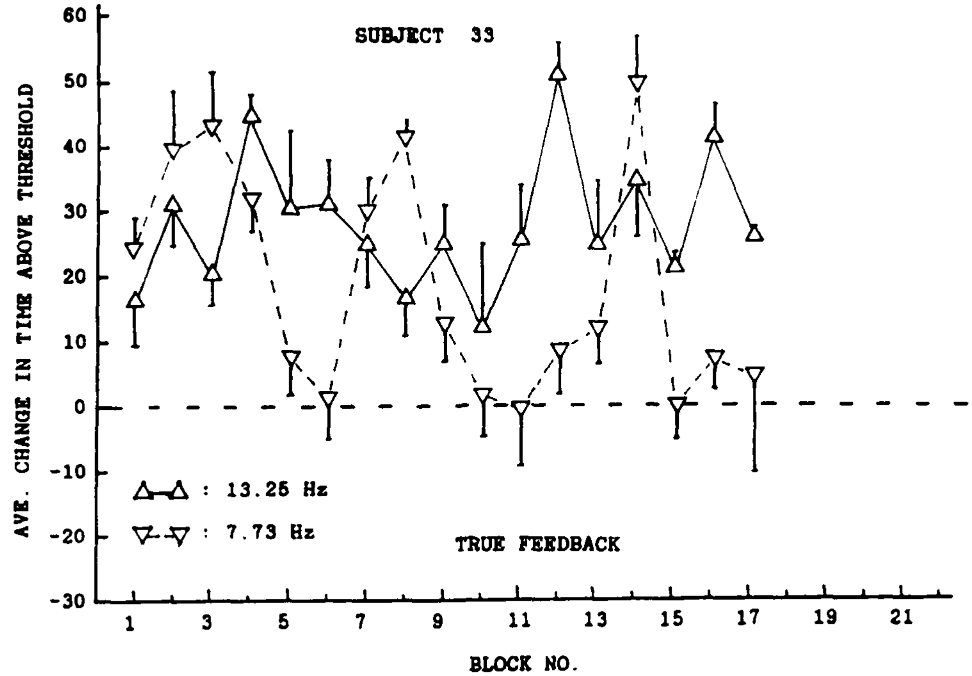


Figure 3.6e. Training results for Subject 06. Note strong time above threshold response and related coherence changes at 13.25 Hz. Note erratic changes in coherence at 7.73 Hz.



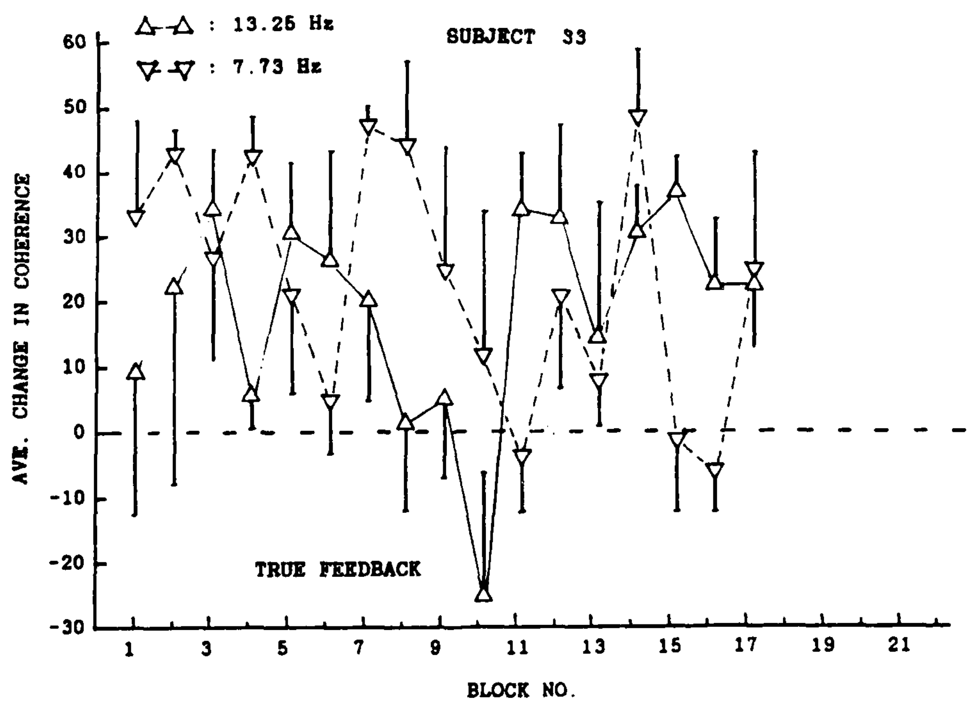


Figure 3.6f. Training results for Subject 33. Note strong response at 13.25 Hz, and erratic response at 7.73 Hz.

were greater than the remnant values for the decision making conditions not only at 9.49 Hz but at 7.73 Hz. These findings suggest that broad band alpha may interfere with the ability to control EEG resonance at 7.73 Hz.

The SSEP results for Subject 04 are similar to those of Subject 13, namely a broad alpha band in their lights only spectrum. Likewise, the time above threshold and coherence values are similar (Figure 3.6c). Subject 04 exhibited little or no control at 7.73 Hz and successful control at 13.25 Hz.

Subject 05 achieved control at 13.25 without corresponding coherence changes (Figure 3.6d). Little control was achieved at 7.73 Hz. As indicated by the SSEP results (Figure 3.1), this Subject was an alpha producer with a broad alpha band and a weak or variable gain response at 7.73 Hz. The trends for this subject are similar to those of Subjects 77 and 04.

Subject 06 exhibited large changes in time above threshold and coherence at 13.25 Hz and at 7.73 Hz (Figure 3.6e). In fact this subject was able to affect average coherence changes as great as 50%. Control was also achieved at 7.73 Hz, however it was inconsistent. Referring back to this subject's SSEP responses (Figure 3.1), some alpha-like response is evident in the remnant spectra. More noteworthy perhaps are the large gain values for the lights only condition at 11.49 and 13.25 Hz, suggesting a strong sensitivity to the evoking stimulus at these frequencies. The large variability in gain response at 7.73 Hz and in the remnant at 7.73 Hz may indicate a sensitive but inconsistent ability to respond to an evoking stimulus at this frequency. This seems to be the case when looking at the average time above threshold and coherence data.

Successful control at both frequencies, especially at 13.25 Hz, was achieved by Subject 33 (Figure 3.6f). Control was erratic at 7.73 Hz. This inconsistent control at 7.73 Hz is similar to that observed for Subjects 03 and 06. Subject 33 would be classified as a non-alpha responder based upon remnant spectra (Figure 3.2). Also noteworthy is the strong gain response for the lights only condition at 13.25 Hz. Not only was this subject a non-alpha producer with a strong loop closure at 7.73 Hz, this subject had a strong evoked response at 13.25 Hz and was able to achieve successful control at 13.25 Hz.

From our SSEP results and loop-closure results for the eight subjects tested, general relationships can be formed. A weak SSEP response would suggest that a subject will have difficulty learning control at that frequency. An SSEP response that exhibits large variability may indicate that successful loop-closure can be easily achieved if the variability is a result of attentional shifts. Non-alpha responders or subjects with weak alpha responses may have an easier time learning to achieve loop-closure at 7.73 Hz.

In an effort to condense the loop-closure results for all eight subjects into one table, the last ten values for time above threshold and coherence were used to compute means and standard deviations for each subject. These results are tabulated in Table 3.2. Subjects were grouped as alpha and non-alpha responders as in Table 3.1. The important finding represented by the table is that, on the average, all subjects exhibited successful control at both 13.25 and 7.73 Hz. This is indicated by the fact that all average times above threshold were positive.

Table 3.2. Mean and standard deviation for each of the last 10 block values for time above threshold and coherence for each of the eight subjects tested.

	AVE. TIME ABOVE				COHERENCE			
	13.25 Hz.		7.73 Hz.		13.25 Hz.		7.73 Hz.	
SUBJ#	MEAN	SD	MEAN	SD	MEAN	SD	MEAN	SD
04	15.42	5.23	2.91	3.31	14.3	9.2	-4.0	9.3
05	13.80	9.70	9.45	9.53	5.7	7.0	1.3	4.4
06	37.87	14.3	18.97	8.01	36.6	14.6	26.4	15.5
13	13.88	11.65	22.61	5.17	27.9	17.5	-1.7	6.7
77	16.51	12.27	5.99	7.51	25.0	12.8	3.4	12.0
03	4.64	3.50	7.12	11.99	2.1	6.9	15.9	14.7
07	31.30	8.05	8.43	10.49	18.4	7.3	0.6	8.3
33	28.02	11.54	13.73	17.38	18.1	19.4	17.3	19.2

4. CONCLUSIONS/FUTURE POSSIBILITIES

From the above results it can be concluded that conscious control of one's EEG at specific frequencies can be achieved, given appropriate feedback. Further, this conscious control can affect the coherence of the response. This has important implications relative to the question of the appropriateness of using the SSEP for mental-state estimation. Our data indicate subjects have the ability to manipulate their EEG levels. This ability is likely to be continually and unpredictably active and without the harnessing effects of feedback may alter SSEPs in an unforeseeable manner. Thus open loop measures may be fraught with uncontrollable changes. A possible solution would be to employ the feedback paradigm reported here during performance so that subjects could be kept continuously aware of their mental state.

A relationship between the subjects' ability to achieve conscious control and subjects' SSEPs were observed. Non-alpha and weak alpha responders appear to have a better facility for control at 7.73 Hz. This may be due to the fact that broad-band alpha resonance of an alpha responder may override one's ability to achieve selective conscious control at 7.73 Hz. This overriding or 'saturation' may be due to some type of broad band alpha masking. It was also observed that weak SSEP responses of a subject may indicate that they will have trouble achieving conscious control at that frequency.

As configured in Figure 2.2, the LAS may be too slow in responding or not sufficiently frequency specific to provide the most effective feedback signal. For large amplitude or large phase changes in the EEG, at the reference frequency, this is probably true. For small perturbations, once a feedback loop has been achieved, LAS response time may be acceptable. This postulation is supported by the positive results of this research effort. Extending the cutoff frequency of the LAS lowpass filters improves the LAS response time but increases the bandwidth resulting in a feedback signal which is too noisy. A possible improvement to the LAS may be the addition of a phase locked loop. In a typical phase locked loop system the reference frequency is made to follow the phase of the incoming signal for stability. Utilizing analog delay lines to shift the phase of the reference sine wave as it drives the light stimulus may achieve the desired effect. The approach would be to delay the sine wave one complete cycle and lead or lag an additional amount, determined by the phase signal of the LAS.

The intention of this approach would be to time-lock the stimulus to the EEG to provide a more effective evoking stimulus so that the visual-cortical system knows it is "looking at itself".

Another improvement to the current LAS configuration would be a method to detect and account for artifacts in the EEG response. The need for this modification was clearly demonstrated by the performance of Subject 13 at 7.73 Hz. (Table 3.2). This subject had the highest average time above threshold with a related average negative coherence, i.e. less coherence with increased resonance. From observation of this subject's EEG spectra during training it was observed that feedback increase was achieved by increasing broad-band alpha. Even after being told that this method of nonspecific control was undesirable Subject 13 was unable to achieve selective control at 7.73 Hz without concurrent control of alpha. Similar control difficulties were encountered by other subjects classified as alpha responders at 7.73 Hz. To prevent nonspecific frequency control and eliminate other broad-band artifact contamination it is proposed that three lock-in amplifiers be used. One lock-in amplifier will be set to a control frequency, as is presently done, and the other two amplifiers will be set to adjacent frequencies on opposite sides of the target frequency. An artifact rejection algorithm will monitor all three channels and generate an appropriate feedback signal. A broad-band response will register equally on all three amplifiers indicating a non-specific EEG potential and resulting in rejection of the broad-band response. In this way inappropriate EEG control by subjects, through manipulation of broad-band alpha for example, will be prevented. Only an 'appropriate' response will be reinforced by the LAS.

With an improved version of the LAS loop-closure system we intend to investigate the relationship that exists between a subject's ability to perform various cognitive tasks and their ability to achieve loop-closure. The approach will be to combine the two tasks with a configuration similar to that of Figure 2.1. Once consistent control at a specific frequency is achieved, ways in which cognitive tasks affect loop-closure ability will be investigated. Perhaps a clear relationship will be found between resource allocation of the cognitive task and particular loop-closure frequencies.

Narrow-band frequency control of one's EEG leads directly to control of brain actuated systems. The controlled gain and/or phase signals could be used as system inputs. In the next phase in our research effort, humans will be trained to follow a slowly moving target with their resonant response using the three channel LAS. As a further step, two humans actuating the same control may be the foundation of brain-to-brain communication.

5. REFERENCES

Erickson, R.P., 1974. Parallel 'population' neural coding in feature extraction. In: Schmitt, F.O., Worden, F.G. (Eds.), The Neurosciences: Third Study Program. Cambridge, Mass. and London, England: The MIT Press, 1974.

Euler, M. and Kiessling, J., 1981. Frequency-following potentials in man by lock-in technique. Electroenceph. Clin. Neurophysiol. 52:400-404, 1981.

Hileman, R.E., and Dick, D.E., 1971. Detection of phase characteristics of Alpha waves in the electroencephalogram. IEEE Trans. Biomed. Eng., Sept. 1971.

Junker, A.M., Levison, W.H., and Gill, R.T., 1987. A Systems Engineering Based Methodology For Analyzing Human Electrocortical Responses. AAMRL-TR-87-030, Armstrong Aerospace Medical Research Laboratories, WPAFB, Ohio, 1987.

Kaufman, L. and Price, R., 1967. The detection of cortical spike activity at the human scalp. IEEE Trans. Biomed. Eng., BME-14(2):84-90, 1967.

Levison, W.H. 1983. Development of a Model for Human Operator Learning in Continuous Estimation and Control Tasks. AFAMRL-TR-83-088, Air Force Aerospace Medical Research Laboratory, WPAFB, Ohio, December 1983.

Levison, W.H., Elkind, J.I., and Ward, J.L. 1971. Studies of Multivariable Manual Control Systems: A Model for Task Interference. NASA CR-1746, May 1971.

Levison, W.H., and Junker, A.M 1978. Use of Tilt Cue in a Simulated Heading Tracking Task. Proceedings of the Fourteenth Annual Conference on Manual Control, Los Angeles,Ca.

Nelson, J.I., Seiple, W.H., Kupersmith, M.J. and Carr, R.E., 1984. Lock-in techniques for the swept stimulus evoked potential. J. Clin. Neurophysiol., 1(4):409-436, 1984.

Pattipati, K.R., Ephraph, A.R., and Kleinman, D.L. 1975. Analysis of Human Decision-Making in Multitask Environments. University of Connecticut, Technical Report EECS-TR-79-15.

Regan, D. 1972. Evoked Potentials in Psychology, Sensory Physiology and Clinical Medicine. Chapman and Hall Ltd., London, SBN 412-100920-4, 1972.

Regan, D. and Cartwright, R.F., 1970. A method of measuring the potentials evoked by simultaneous stimulation of different retinal regions. Electroenceph. Clin. Neurophysiol., 28:314-319, 1970.

Spekreijse, H. 1966. Analysis of EEG Response in Man Evoked by Sine Wave Modulated Light. Dr. W. Junk Publishers. The Hague, Netherlands. 152 pp.

Wilson, G.F. and O'Donnell, R.D. 1980. Human Sensitivity to High Frequency Sine Wave and Pulsed Light Stimulation as Measured by the Steady State Cortical Evoked Response. Technical Report AFAMRL-TR-80-133.

* U.S. GOVERNMENT PRINTING OFFICE 1980 - 548-002/80202